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Quantifying and predicting interseeded legume establishment in winter cereals

Brock Cameron Blaser
Iowa State University

Quantifying and predicting interseeded legume establishment in winter cereals

by

Brock Cameron Blaser

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Program of Study Committee:

Lance R. Gibson, Co-Major Professor
Jeremy W. Singer, Co-Major Professor
Stephen K. Barnhart
Matt Liebman
Robert P. Anex

Iowa State University

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Chapter 1: General Introduction

Incorporation of winter cereal grains into the North Central USA corn (*Zea mays* L.)/soybean [*Glycine max* (L.) Merr.] rotation could improve yields of subsequent crops (Crookston et al., 1991), reduce erosion (Zhu et al., 1989), and serve as a companion crop for small seeded legume establishment (Blaser et al., 2006; Singer et al., 2006). Forage legume intercrops can provide high quality feed for livestock (Blaser et al., 2007), suppress weeds (Mutch et al., 2003; Blaser et al., 2006), and provide nitrogen for subsequent crops (Hesterman et al., 1992). Winter cereal grain/legume intercrops managed for maximum grain and legume production have been successful in the North Central USA (Hesterman et al., 1992; Mutch et al., 2003; Blaser et al., 2006; Singer et al., 2006).

Management practices that increase cereal canopy growth have been reported to limit legume productivity. When cereal seeding rate was increased from 100 to 400 seeds m^{-2}, Blaser et al. (2007) reported a 30% decrease in red clover (*Trifolium pratense* L.) dry matter (DM) 40 d after cereal harvest. They suggested the decreased DM was caused by management practices that altered light transmittance to the red clover, but never addressed the possibility that improved cereal growing conditions could result in a more competitive companion crop. Light transmittance through the cereal canopy to the legume is a critical factor influencing legume survival and productivity (Klebesadel and Smith, 1959). Therefore, understanding factors that influence light transmittance, such as cereal canopy traits, crop management practices, and the interaction of other abiotic and biotic factors, could lead to improved intercrop management strategies with potential to maximize this system.

Cereal grain/legume intercrops have been included in previous crop management studies, yet researchers focused only on main crop yields, N contribution from the legume, or weed suppression, and provided little data about legume establishment or post-harvest productivity (Brandt et al., 1989; Singer and Cox, 1998; Legere et al., 2001). Singer and Cox (1998) evaluated tillage practices in a corn-soybean-wheat (*Triticum aestivum* L.)/red clover rotation, yet they did not discuss or quantify red clover productivity and cited red clover establishment as a major production challenge in this rotation.

The goal of this research was to focus on legume establishment in a winter cereal/legume intercrop by quantifying cereal canopy traits that influence legume productivity and identifying soil management practices that maximize legume establishment and DM. By quantifying cereal canopy traits and measuring their effect on legume productivity, prediction models could be developed to estimate post-harvest legume densities prior to grain harvest. These estimates would give producers critical information in making management decisions and provide producers and researchers a greater understanding of the interactions occurring within this intercrop as they strive to maximize crop production.

Dissertation Organization

This dissertation is organized in journal manuscript format. Chapter 1 is a general introduction and description of the dissertation content. Chapter 2 is a manuscript to be submitted to *Agronomy Journal* reporting agronomic results from a study evaluating winter cereal canopy effects on interseeded legumes. Chapter 3 will also be submitted to *Agronomy Journal* to report the results of a winter cereal/legume intercrop response to three tillage systems and a soil amendment. Chapter 4 is a manuscript to be submitted to *Field Crops Research* reporting the development and validation of a model to predict post-harvest legume densities established by frost-seeding into winter cereals. Chapter 5 contains the general conclusions and summary of this research.

Authors listed on the three manuscripts include Brock C. Blaser, Lance R. Gibson, Jeremy W. Singer, Stephen K. Barnhart, Matt Liebman, Robert P. Anex, and Garritt L. Page. PhD candidate, Mr. Brock C. Blaser, designed and implemented the experiments, collected and analyzed the data, and wrote the content found in the manuscripts. Drs. Lance R. Gibson and Jeremy W. Singer served as co-major professors to Mr. Blaser and provided oversight and input into the research, analysis, and writing. Drs. Stephen K. Barnhart, Matt Liebman, and Robert P. Anex served as program of study committee members. Mr. Garritt L. Page provided critical statistical support for analyses performed in Chapter 4.

Chapter 2: Diverse Winter Cereal Grain Canopies Influence Interseeded Legume Establishment and Productivity

A paper to be submitted to *Agronomy Journal*

Brock C. Blaser,* Lance R. Gibson, Jeremy W. Singer, and Stephen K. Barnhart

ABSTRACT

Interseeding red clover (*Trifolium pratense* L.) or alfalfa (*Medicago sativa* L.) into winter cereals in the North Central USA can provide forage and a green manure crop. We hypothesize that winter cereal canopy traits such as leaf area index (LAI) and whole plant dry matter (DM) influence interseeded legume establishment and productivity, yet the effect of canopy traits on resource competition in interseeded systems is not well understood. This study was conducted from 2005 to 2007 to evaluate the impact of diverse cereal canopy traits on the establishment of frost-seeded legume intercrops. In March, red clover and alfalfa were frost-seeded into three winter wheat (*Triticum aestivum* L.) and three triticale (X *Triticosecale* Wittmack) varieties selected based on LAI, plant height, DM, and maturity date. Across three growing seasons, the cereals produced a range of LAI from 2.1 to 6.2 and whole plant DM at harvest of 817 to 2029 g m^{-2}. Legume densities were influenced by cereal in one year and legume DM was influenced by cereal in two years. Alfalfa and red clover densities were similar, yet DM production was 42% higher in red clover 40 d after harvest. The presence of a legume intercrop did not affect grain yield or yield components, but reduced weed densities and DM 40 d after grain harvest. Producers implementing this intercrop system may select cereal varieties based on grain yield, but must also be cautious of varieties known to produce maximum LAI values above 5.6 because they have the potential to reduce legume productivity.

INTRODUCTION

Incorporating winter cereal grains into the North Central USA corn (*Zea mays* L.)/soybean [*Glycine max* (L.) Merr.] system could extend the rotation and increase yields of subsequent crops (Crookston et al., 1991; Singer and Cox, 1998), build soil tilth (Brady and Weil, 2000), reduce erosion (Zhu et al., 1989), and improve nitrogen capture (Nance et al., 2007). Addition of a legume intercrop decreases the fallow period after grain harvest, provides a forage crop to utilize solar energy (Singer et al., 2007), and provides N to subsequent crops as a green manure (Hesterman et al., 1992). The presence of forage during the traditional fallow period has also been reported to harbor beneficial insects (Hartwig and Ammon, 2002) and suppress weed growth (Mutch et al., 2003; Blaser et al., 2006).

Red clover has been successfully frost-seeded into winter cereals (Hesterman et al., 1992; Blaser et al., 2006; Singer et al., 2006). However, winter cereal species effects on the interseeded legume have been reported by Blaser et al. (2006), who found that triticale lowered red clover post-harvest plant density 18% compared with wheat in one of two years. Conversely, interseeded legume effects on grain yields have been inconsistent. Winter wheat yields were reduced an average of 43% with interseeded subterranean clover (*Trifolium subterraneum* L.) compared to wheat alone in one of three years, were 48% higher than interseeded plots in another year, and were similar in a third year (Brandt et al., 1989).

Tesar and Marble (1988) claimed that using winter cereals as companion crops for alfalfa establishment was less effective because winter cereals were too competitive compared to spring cereals. To better understand the intercrop relationship and select cereal varieties that are compatible with red clover and alfalfa establishment, canopy traits that impact legume productivity must be quantified. Light transmittance to the legume was reported to be a critical factor limiting legume establishment as an intercrop (Klebesadel and Smith, 1959) and is directly influenced by measurable canopy traits. We hypothesized that as canopy traits such as LAI and whole plant DM increased, interseeded legume productivity would decrease. Therefore our objectives were to 1) quantify the LAI and whole plant DM of six winter cereals exhibiting diverse canopies, and 2) measure the impact of these traits on interseeded red clover and alfalfa establishment and productivity.

MATERIALS AND METHODS

This winter cereal grain/legume intercrop study was conducted from 2005-2007 at the Iowa State University Agronomy and Agricultural Engineering Farm near Ames, IA (42º 00'N, 93º 50'W; elevation 341 m above sea level). Treatments were arranged as a split-block with four replicates with cereal grain varieties as main plots and legume varieties as subplots.

'Décor', 'Lamberto', and 'NE426GT' winter triticale varieties and 'Ernie' and 'Kaskaskia' soft red and 'Goodstreak' hard red winter wheat varieties were no-till planted into recently harvested soybean fields with Nicollet loam (fine-loamy, mixed, superactive, mesic aquic hapudolls) soil in 2005 and 2007 and Webster loam (fine-loamy, mixed, superactive, mesic typic endoaquolls) soil in 2006. Cereal varieties were selected to provide a broad range of canopy characteristics including maximum LAI (3.4 to 4.7) and plant heights (96 to 132 cm) based on previous studies (Skrdla and Jannink, 2004; Iutzi, 2006). The cereals were planted at 300 PLS m^{-2} on 5 Oct. 2004, 7 Oct. 2005, and 6 Oct. 2006 using a tractor-mounted 3.8 m wide John Deere 1520 grain drill (John Deere Co., Moline, IL) with 15 cm row widths. The planted area for each cereal grain variety was 7.6 x 30 m.

In 2005, 'Cherokee' red clover was frost-seeded in subplots within each cereal grain variety plot on 23 March. 'Marathon' red clover and 'Mycogen 4375LH' alfalfa were frost-seeded on 29 March. In 2006 and 2007 all three legumes were frost-seeded on 15 March and 20 March, respectively. Legumes were seeded at 900 PLS m^{-2} using a tractor-mounted, 3.66 m wide Gandy Model #1012T-TBM drop spreader (Gandy Co., Owatonna, MN). Due to no seed supply in 2007, Cherokee was replaced with the genetically similar red clover variety 'Southern Belle' (Quesenberry et al., 2005). Southern Belle was developed through a combination of recurrent selection processes using Cherokee as the base population and initial production trials reported similar yields between the two varieties. Cherokee and Marathon were selected for high DM production and diversity in origin, below 38° North and Wisconsin, respectively (Singer et al., 2006). Mycogen 4375LH alfalfa (hereafter referred to as alfalfa), a commercially available and locally adapted variety with a fall dormancy rating of 3.8, was included to evaluate frost-seeded alfalfa establishment success under winter cereals managed for grain. A fourth subplot within each cereal grain variety was a check plot with no legume seeded. Each subplot area occupied 7.6 x 7.3 m. All plots were broadcast fertilized with 45 kg N ha^{-1} in the form of NH_4NO_3 on 4 Apr. 2005, 29 Mar. 2006, and 9 Apr. 2007. In 2006, 60 kg P ha^{-1} in the form of P_2O_5 was also applied on 29 March.

Cereal Canopy and Dry Matter Measurements

Cereal canopy LAI was measured every 18 d beginning at jointing [growth stage (GS) 30; Zadoks et al., 1974] through grain harvest. These measurements were initiated on 21 Apr. 2005, 24 Apr. 2006, and 4 May 2007. Data were obtained using the LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE) by placing the light sensor in the interrow of two untrafficked grain rows and just above the legume canopy. One above (incident) and two below canopy measurements were taken in each subplot.

Two aboveground cereal DM samples were collected from each cereal grain subplot when the cereal grains reached full head extension (FHE) and grain maturity (GS 92). Full head extension samples were collected on 7 June 2005, 5 June 2006, and 11 June 2007. Time of FHE was determined when the apical growth ceased. Plant heights were measured using a 0.25 m^2 circular transparent disk and the method described by Oleson et al. (2004). Grain maturity was determined when grain kernels reached the kernel hard stage (GS 92). Plant DM samples at grain maturity were collected on 12 July 2005, 10 July 2006, and 11 July 2007. With both samplings, the cereal DM was clipped at the soil surface from two 0.5 m^2 quadrats per subplot. Samples were oven dried at 60°C until constant weight and a whole sample DM weight was recorded.

Cereal Yield and Yield Components

All yield and yield components were measured from the DM samples collected at grain maturity. Spikes m^{-2} was counted prior to threshing the grain. The threshed grain sample was weighed to determine subplot grain yield and 1000-kernel weight from two random subsamples. Kernels $spike^{-1}$ for each cereal species was calculated from the total yield, spikes m^{-2}, and 1000-kernel weight data. Whole grain moisture was measured by drying 10 g of grain at 130ºC for 19 h and weighing (ASAE Method S352.2). Final subplot grain yield was reported on a 135 g kg^{-1} moisture basis. The harvest index (HI) was calculated as grain dry weight divided by total aboveground DM.

A 30 g subsample of grain was ground using an Udy cyclone sample mill (Udy Corp., Ft. Collins, CO) to pass a 0.5 mm screen. Moisture content of the ground grain subsample was determined by drying 2 to 3 g of ground grain at 130ºC for 1 h and weighing (AACC Method 44-15A). Ground grain samples were analyzed for N concentration using the Dumas combustion method (AOAC Method 990.03). Percent crude protein was calculated from total N multiplied by the factor of 5.7 for wheat or 6.25 for triticale and was adjusted for moisture content.

All six cereal varieties were machine harvested using a Massey Ferguson Model 25 combine (Sampo Rosenlew Ltd., Pori, Finland) on the same day, regardless of maturity date. Harvests occurred on 13 July 2005, 17 July 2006, and 13 July 2007. The straw was baled and removed the day of grain harvest. After the straw was baled in 2005 and 2006, a forage harvester was used to cut excess stubble to 6 cm. In 2007, the stubble height after combining was 6 cm, so no additional stubble management was necessary.

Legume and Weed Density and Dry Matter

Legume plant densities were measured prior to cereal grain harvest by counting the plants within one 0.5 m^2 quadrat per subplot on 8 July 2005, 14 July 2006, and 10 July 2007. Legume shoot DM was determined 40 d after grain harvest by clipping plants 6 cm above the soil surface from two 0.25 m^2 quadrats per subplot. These samplings occurred on 22 Aug. 2005, and 25 Aug. 2006 and 2007. Weed density and DM 40 d after grain harvest was collected at the same time and from the same 0.25 m^2 quadrats as the 40 d legume DM. Both legume and weed DM samples were oven dried at 70ºC until constant weight.

Weather Data

Weather conditions during the study and long-term climatic data were obtained from the Iowa Environmental Mesonet (IEM, 2008). Daily maximum and minimum air temperature and rainfall totals were recorded from a weather station located 0.5 km from the experimental site (Table 1). Growing degree days (GDD) were calculated beginning March 1 of each season using the formula: GDD = Σ {[(daily max. temp. + daily min. temp.) / 2] – base temp.} > 0 with base temperature = 0ºC. Between frost-seeding on 20 Mar. 2007 and 3 Apr. 2007, observed average daily air temperature was 13°C and total rainfall was 58 mm.

These optimum growing conditions resulted in a high percentage of legume germination. From 4 to 9 Apr. 2007, a severe frost event was observed with average daily temperatures of -3.2°C and average low temperatures of -8.1°C. Damage to both cereals and legumes was observed and the few legume plants that survived or germinated after the frost event were not adequate for data analysis. Consequently, no legume data are presented for 2007.

Statistical Design and Analysis

The experimental design was a randomized complete block in a split-block treatment arrangement. Statistical analysis was performed using PROC MIXED of the Statistical Analysis System Version 9.1 (SAS Institute, Cary, NC). A Fisher's protected LSD (α = 0.05) was used for all mean separation. Year, variety, and legume were treated as fixed effects. Initial analyses resulted in a significant year effect, so all data are presented by year. The linear model was $Y_{ijk} = \mu + B_i + V_j + BV_{ij} + L_k + BL_{ik} + VL_{jk} + BVL_{ijk}$, where B represented blocks or replicates, V represented cereal variety, and L represented legume variety.

RESULTS AND DISCUSSION

Cereal Grain Production

In 2005, grain yields ranged from 3.71 to 5.61 Mg ha^{-1} (Table 2). NE426GT triticale and Kaskaskia wheat were the highest yielding varieties and Décor triticale and Ernie wheat were the lowest. Grain yields were similar among varieties in 2006 with an average of 6.31 Mg ha^{-1}. This average was 30% higher than the 2005 average grain yield and 47% higher than the 2007 yields. In 2007, maximum grain yields were observed from Décor and Kaskaskia with 4.04 and 3.83 Mg ha^{-1}, but the six varieties averaged only 3.34 Mg ha^{-1}. The substantially higher grain yields in 2006 were related to the drier conditions during the grain filling period which was ideal for increased kernel weight and number (Tables 1 and 2). Similar dry conditions occurred in 2007, but yields were limited by cereal grain stands damaged by frost in early April. Average wheat and triticale yields were 0.97 Mg ha^{-1} lower in 2005, 0.91 Mg ha^{-1} higher in 2006, and 2.16 Mg ha^{-1} lower in 2007 compared to seven and three year wheat and triticale averages recorded in Iowa (Skrdla and Jannink, 2004).

The three wheat varieties averaged 36% more spikes m^{-2} than the three triticale varieties in both 2005 and 2006, while the trend was reversed for kernels $spike^{-1}$ in both years (Table 2). Triticale varieties averaged 38 and 26% more kernels $spike^{-1}$ than wheat varieties in 2005 and 2006. Thousand-kernel weight did not follow a species trend as the highest weights were recorded for Goodstreak and NE426GT in 2005 and Ernie and Décor in 2006. No cereal grain yield component differences were observed in 2007. Décor had the highest grain protein content of all six varieties in 2005 and 2007 with 15.9 and 14.0 g kg^{-1}, while 2006 grain protein differences among species were minor (Table 2). When interseeding subterranean clover into winter wheat, Brandt et al. (1989) reported both a grain yield increase and decrease in the presence of the legume in separate years. The legume intercrop also caused a significant increase in kernels $spike^{-1}$ and spike m^{-2} in one year and lower grain N concentration in a separate year. However, the presence of a legume intercrop in this study had no effect on grain yield, yield components or grain protein.

Cereal Grain Canopy

Cereal grain whole plant DM was collected when plants reached FHE and maturity (GS 92) just prior to grain harvest. In 2005, NE426GT and Lamberto produced the greatest DM at FHE with an average of 1420 g m^{-2} (Table 3). In 2007, the greatest DM was produced by Goodstreak and NE426GT with an average of 892 g m^{-2}. Décor and Ernie produced the least DM in 2005 with 1163 and 1029 g m^{-2} and again in 2007 with 552 and 615 g m^{-2}, respectively. No differences among varieties were observed for FHE DM in 2006. Observed whole plant DM averages for wheat and triticale were similar to average winter triticale DM reported by Gibson et al. (2007) and Schwarte et al. (2005) who used similar triticale varieties in central Iowa from 2003-2005.

Average DM increase from the FHE to maturity DM harvest was 8% in 2005 and 2007 and 47% in 2006 (Table 3). This follows closely with the differences detected in grain yield and supports the physiological concept that more plant biomass potentially results in increased grain yields under optimum growing conditions.

Ernie, Kaskaskia, and NE426GT averaged a 19% greater HI compared to the average of Goodstreak, Décor, and Lamberto in 2005 (Table 3). In 2006, Lamberto had a 13% lower HI than all other varieties. More dramatic differences were observed in 2007 because of the variability in crop stands. Ernie and Décor averaged a HI of 0.59 compared to the lowest two varieties, Goodstreak and NE426GT, averaging 0.31. A cereal variety x legume interaction was observed for HI in 2005 when Ernie produced a 0.08 higher HI and NE426GT produced a 0.07 lower HI in subplots containing Marathon red clover compared to the other cereals and legume treatments.

Leaf area index measurements were initiated at jointing (GS 31) which occurred in late April in 2005 and 2006 (430 GDD) and early May 2007 (570 GDD; Fig. 1). In 2005, all varieties surpassed an LAI of 4.0 by 630 GDD and obtained maximum values between 4.5 and 6.2 near the end of May. Lamberto had significantly higher values throughout the season, averaging 0.8 higher LAI than Goodstreak and NE426GT. Average maximum LAI values in 2006 were 3.9 with Lamberto, Ernie, and Goodstreak exceeding 4.0 for a brief period at 980 GDD. Maximum LAI values in 2007 averaged 2.8. Goodstreak had the maximum LAI for the season averaging 0.4 greater LAI than the next closest variety, NE426GT. Due to the crop stand reduction from the spring frost, no varieties produced LAI values comparable to the previous two seasons.

All varieties produced maximum LAI near anthesis (GS 69) each season. Leaf area index started to decline as nutrients were remobilized from vegetative to reproductive growth. However, when comparing the LAI and grain yield in 2005 and 2006, the higher LAI in 2005 did not result in higher grain yields compared with 2006, which could be attributed to rainfall events in both years (Table 1 and 2; Fig. 1). When compared with optimum irrigation for winter wheat, Day and Intalap (1970) reported a 48% yield loss when water was limited during jointing (GS 30). Below average rainfall in March and April 2005 corresponded to jointing of the cereals in this study and may have limited grain yield potential. Day and Intalap (1970) also reported a 42 and 37% yield loss when water was limited during flowering (GS 69) and soft dough (GS 85), respectively. The time period for flowering and soft dough in 2006 also corresponded to below average rainfall in May and June. However, normal rainfall amounts for central Iowa have been reported to limit winter cereal yield in other years (Skrdla and Jannink, 2004; Schwarte et al., 2005; Blaser et al., 2006). Therefore, below normal rainfall in May and June, combined with 15 and 28% above normal rainfall in March and April, may have provided sufficient soil moisture for cereal growth without limiting cereal yields in 2006.

The six winter cereals combined with the three unique growing seasons produced a wide range of canopies. Maximum LAI values ranged from 6.2 in 2005 to 2.1 in 2007 (Fig. 1) and whole plant DM at harvest averaged 1136, 2029, and 817 g DM m^{-2} in for 2005-2007. Because these broad ranges were achieved, it was possible to evaluate the impact of these canopy traits on legume establishment and productivity.

Legume Establishment and Dry Matter

Legume density at grain harvest was only different among cereal varieties in 2005 and was caused by lower densities recorded under Lamberto (Table 4). This observation corresponded to higher FHE DM and LAI produced by Lamberto throughout the season (Table 3 and Fig. 1). Legume densities were affected by legume species and variety in 2005 and 2006 (Table 4). Marathon red clover had 31 and 48% higher densities than Cherokee red clover in both years. Alfalfa plant counts in both years resulted in mean densities between and statistically similar to both red clover varieties in 2005 and only to Cherokee in 2006. Previous reports claimed using winter cereals as companion crops for alfalfa to be less effective because winter cereals were too competitive compared to spring cereals (Tesar and Marble, 1988). Results from this study demonstrate that alfalfa is as competitive as Cherokee and Marathon red clover varieties and can be successfully frost-seeded into winter cereals grown for optimum grain production.

Cereal variety affected legume DM production 40 d after grain harvest in 2005 and 2006. This residual effect of the cereal crop on legume production is most likely attributed to the cereal canopy which affected legume shoot and root size during the intercrop period. In 2005, legume DM from treatments previously containing Lamberto, Goodstreak, and NE426GT was lower than the other cereals (Table 4). This response may be explained by the higher LAI values produced by these three varieties throughout the season (Fig. 1). Higher LAI canopies permit less light transmittance to the legume seedlings and may result in less plant growth and root development. A similar pattern was observed in 2006 when Lamberto produced the same or higher LAI relative to Ernie, Kaskaskia, Goodstreak, and Décor, and legume DM collected after Lamberto produced an average of 35% less DM relative to those four cereals (Table 4). Leaf area index for NE426GT was similar to Lamberto for over half of the season, which resulted in similar 40 d legume DM (Fig. 1; Table 4).

Legume shoot DM production was also affected by legume variety and species in 2005, yet legume density did not directly influence DM production. Cherokee had the lowest density of the three legumes but produced the greatest DM with 195 g m^{-2} (Table 4). Marathon produced 12% less DM than Cherokee and on average, the two red clovers produced 42% more DM than alfalfa. Legume DM production independent of density was also observed by Singer et al. (2006). They reported that the relationship between red clover plant number and DM at cereal harvest was not significant in a year with high red clover plant counts (average of 229 plants m^{-2}), but was highly significant in a year with low red clover plant counts (average of 30 plants m^{-2}) at cereal harvest.

Weed Density and Dry Matter

Cereal variety did not influence weed densities 40 d after harvest in any of the three study years. However, the presence of a legume reduced weed densities on average by 65% compared to the no legume check plot in 2005 and 2006 (Table 4). Additionally, legume presence reduced weed DM 68 and 38% in 2005 and 2006. Similar results were reported by Blaser et al. (2006) who reported a 38% reduction in weed density for treatments containing red clover compared with a no legume treatment.

A cereal variety x legume interaction was observed in 2005 due to a large quantity of weed DM produced in a check subplot of Ernie. This subplot produced 146 g m^{-2} compared to an average of 87 g m^{-2} for the check subplot of the other five cereals. In 2007, 40 d weed DM was affected by previous cereal variety. Goodstreak lowered weed DM 51% compared to the average of the other five cereals. Goodstreak produced higher LAI throughout the 2007 growing season and even 40 d after removal of the cereal, the competition effect was still apparent.

CONCLUSIONS

Winter cereal LAI values ranged from 3.5 to 6.2 for 2005 and 2006 and had a limited effect on legume establishment densities, except when LAI values were sustained over 5.6

for nearly 40 consecutive days. Legume DM was affected by cereal variety 40 d after grain harvest, but responses were not always related to legume density. Alfalfa frost-seeded into winter cereal grains in the North Central U.S. can achieve similar establishment densities as red clover, but may experience slightly lower DM yields in the establishment year. Weed density and DM are consistently suppressed in the presence of legumes in fields typically fallow after grain harvest. Plant breeders developing cereals compatible with interseeded legumes and producers using this intercrop may continue to focus on high grain yield in their selection processes. However, attention must be given to varieties known to produce maximum LAI values above 5.6 because of their potential to reduce legume productivity.

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Figure 1. Average seasonal leaf area index (LAI) for Ernie and Kaskaskia soft red and Goodstreak hard red winter wheat, and Décor, Lamberto, and NE426GT winter triticale grown near Ames, IA from 2005 to 2007. Vertical bars represent LSD (0.05) values comparing means within a specific year and measurement date. GDD = Σ {[(daily max. temp. + daily min. temp.) / 2] – base temp.} >0 with base temperature = 0ºC.

Table 1. Average monthly air temperature and rainfall near Ames, IA† for 2005-2007. Thirty-year averages (30-yr) were computed from data collected approximately 0.5 km from the experimental site from 1975-2004.

	Air temperature				Rainfall			
Month	2005	2006	2007	30-yr	2005	2006	2007	30-yr
	°C				mm			
March	3.0	3.3	6.0	2.8	35	74	81	53
April	12.8	13.1	8.7	10.3	82	109	153	93
May	15.5	17.0	19.0	16.5	111	55	169	112
June	23.0	22.1	22.2	21.4	124	21	52	119
July	24.1	24.4	23.8	23.5	104	141	75	112
August	22.1	22.6	24.1	22.1	172	156	200	120

†NWS COOP site Ames 8WSW.

Table 2. Winter cereal variety means for grain yield, yield components, and protein content near Ames, IA from 2005-07.

Variety†	Grain yield‡	Spikes m^{-2}	Kernels $spike^{-1}$	1000 kernel wt.	Grain protein
	Mg ha^{-1}	—— no.	——	g	g kg^{-1}
			2005		
Ernie	3.71	879	18	24.2	12.7
Kaskaskia	5.00	643	28	27.9	12.3
Goodstreak	4.37	815	19	28.7	14.3
NE426GT	5.61	530	38	29.0	13.1
Décor	3.82	397	33	29.7	15.9
Lamberto	4.14	558	33	23.0	14.3
LSD (0.05)	0.49	66	4	1.5	0.8
			2006		
Ernie	6.33	769	22	38.4	10.6
Kaskaskia	6.67	578	34	34.4	11.3
Goodstreak	6.73	760	27	33.0	12.3
NE426GT	6.16	439	38	36.8	11.7
Décor	6.32	409	39	39.3	10.9
Lamberto	5.67	496	35	32.1	11.7
LSD (0.05)	NS§	53	3	1.9	1.1
			2007		
Ernie	3.21	492	26	28.1	11.7
Kaskaskia	3.83	481	29	29.6	11.1
Goodstreak	3.02	400	28	28.1	12.1
NE426GT	3.04	524	22	28.0	12.1
Décor	4.04	422	34	28.9	14.9
Lamberto	2.95	382	29	28.4	13.1
LSD (0.05)	0.80	NS	NS	NS	0.6

† Ernie and Kaskaskia are soft red winter wheat, Goodstreak is hard red winter wheat, and NE426GT, Décor, and Lamberto are winter triticale.
‡ Cereals harvested on 12 July 2005, 10 July 2006, and 11 July 2007.
§ NS, not significant.

Table 3. Winter cereal whole plant dry matter (DM) at full head extension (FHE) and grain maturity, and harvest index (HI) near Ames, IA from 2005-07.

	2005			2006			2007		
Variety†	FHE DM†	Maturity DM§	HI	FHE DM	Maturity DM	HI	FHE DM	Maturity DM	HI
	—— g m^{-2} ——			—— g m^{-2} ——			—— g m^{-2} ——		
Ernie	1029	1069	0.35	1050	1898	0.33	615	562	0.58
Kaskaskia	1210	1336	0.38	1073	2082	0.32	853	860	0.45
Goodstreak	1295	1413	0.31	1133	2196	0.31	912	934	0.32
NE426GT	1416	1619	0.36	1102	2002	0.31	871	998	0.30
Décor	1163	1309	0.29	1057	2011	0.31	552	716	0.59
Lamberto	1423	1461	0.28	1011	1986	0.28	702	829	0.36
LSD (0.05)	116	150	0.03	NS¶	153	0.02	56	81	0.11

† Ernie and Kaskaskia are soft red winter wheat, Goodstreak is hard red winter wheat, and NE426GT, Décor, and Lamberto are winter triticale.
‡ FHE DM sampled on 7 June 2005, 5 June 2006, and 11 June 2007.
§ Maturity DM sampled on 12 July 2005, 10 July 2006, and 11 July 2007.
¶ NS, not significant.

Table 4. Frost-seeded Cherokee and Marathon red clover (RC) and Mycogen 4375LH alfalfa densities at grain harvest and legume dry matter (DM), weed densities and DM 40 d after grain harvest near Ames, IA from 2005-06.

	2005				2006			
	Legume density†	Legume DM‡	Weed density	Weed DM	Legume density	Legume DM	Weed density	Weed DM
	plants m^{-2}	g m^{-2}	plants m^{-2}	g m^{-2}	plants m^{-2}	g m^{-2}	plants m^{-2}	g m^{-2}
Variety§								
Ernie	53	191	12	59	148	185	5	28
Kaskaskia	61	190	13	47	147	198	4	13
Goodstreak	57	122	13	43	158	187	4	9
NE426GT	53	141	16	50	169	167	3	11
Décor	60	199	13	39	140	188	5	22
Lamberto	35	101	17	45	105	123	5	17
LSD (0.05)	15	52	NS¶	NS	NS	47	NS	NS
Legume								
Alfalfa	55	106	13	42	140	151	4	13
Cherokee RC	43	195	6	25	100	185	2	9
Marathon RC	62	171	10	26	194	188	2	4
Check	-	-	26	97	-	-	8	42
LSD (0.05)	13	23	10	27	50	NS	2	16

† Legume densities counted on 8 and 14 July 2005 and 2006.

‡ Legume DM, weed densities and DM counted and sampled on 22 and 25 Aug. 2005 and 2006.

§ Ernie and Kaskaskia are soft red winter wheat, Goodstreak is hard red winter wheat, and NE426GT, Décor, and Lamberto are winter triticale.

¶ NS, not significant.

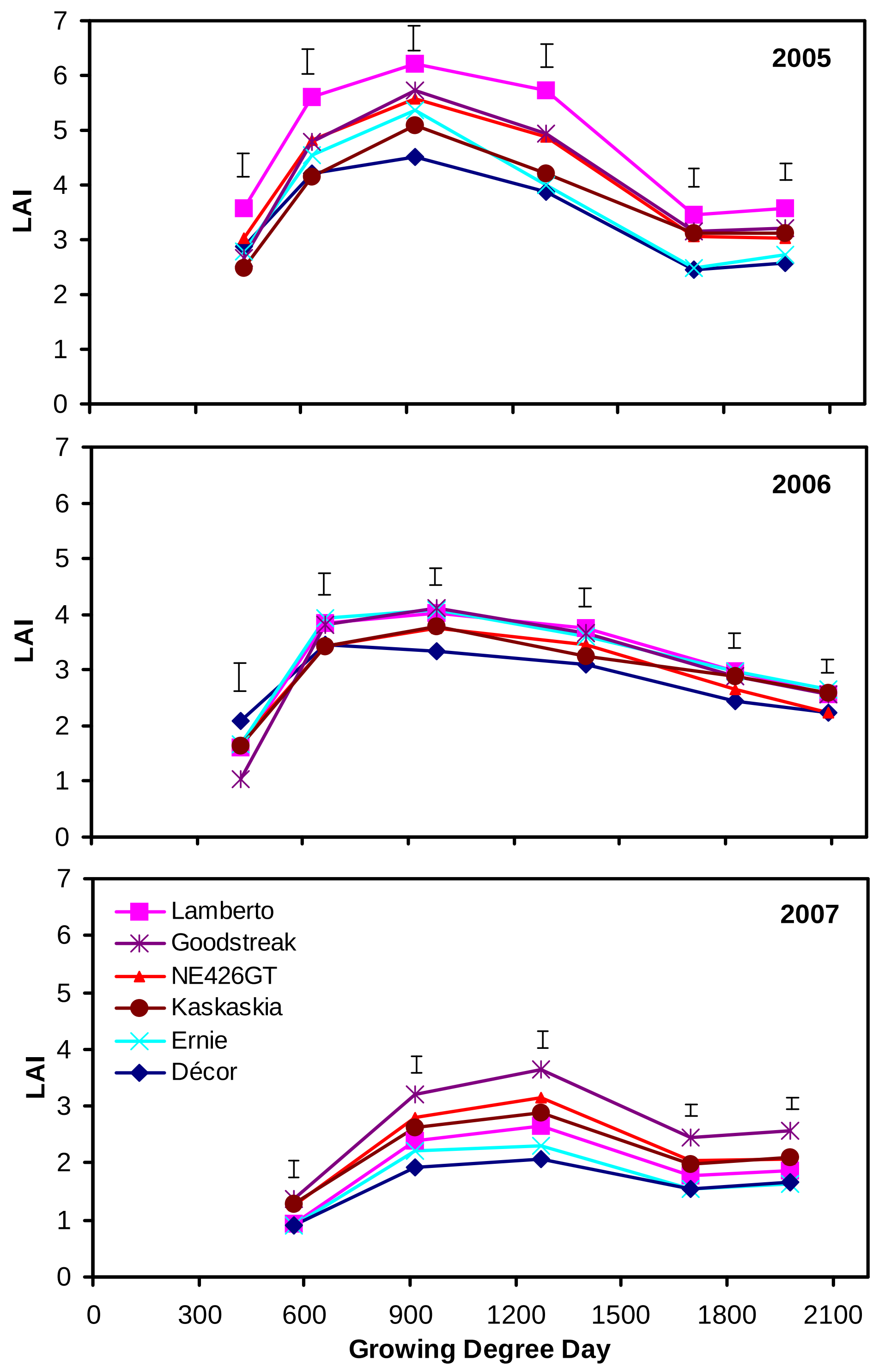

Figure 1. Average seasonal leaf area index (LAI) for Ernie and Kaskaskia soft red and Goodstreak hard red winter wheat, and Décor, Lamberto, and NE426GT winter triticale grown near Ames, IA from 2005 to 2007. Vertical bars represent LSD (0.05) values comparing means within a specific year and measurement date. GDD = Σ {[(daily max. temp. + daily min. temp.) / 2] – base temp.} >0 with base temperature = 0ºC.

Chapter 3: Tillage and Compost Effects on Winter Wheat/Red Clover Intercrop Establishment and Productivity

A paper to be submitted to *Agronomy Journal*

Brock C. Blaser,* Jeremy W. Singer, and Lance R. Gibson

ABSTRACT

Frost-seeding red clover (*Trifolium pratense* L.) into winter cereals is generally considered an efficient and cost-effective method of establishment, yet information regarding establishment under different soil management practices is limited. Intensive tillage (IT), moderate tillage (MT), and no-tillage (NT) with and without compost amendment in a corn (*Zea mays* L.)-soybean [*Glycine max* (L.) Merr.]-wheat (*Triticum aestivum* L.)/red clover rotation were used to test the response of red clover establishment to soil management. Wheat yields were higher in IT and MT compared with NT in one year, higher in NT than IT and MT in a second year, and similar across tillage treatments in two other study years. Higher grain yield in IT corresponded to lower red clover densities at wheat harvest in one of three years. Red clover plant densities at wheat harvest were higher under NT and MT compared with IT in one year and were 41% lower with compost 40 d after wheat harvest of the same year. Red clover shoot dry matter (DM) at wheat harvest and 40 d after harvest averaged 70% higher when grown without compost in one year. Red clover plants preferentially established in the row of the wheat stand two of three years (row 56% > than interrow). Wheat and red clover under MT consistently performed equal to or greater than NT or IT. Producers using this intercrop may reduce tillage without affecting red clover densities and DM, but may sacrifice some red clover DM to achieve optimum grain yield.

INTRODUCTION

Winter cereal grain/legume intercrop systems are viable options for extending the corn/soybean cropping system in the North Central USA. Extending this crop rotation with a wheat/red clover intercrop may increase yields of subsequent crops (Crookston et al., 1991), reduce soil erosion (Zhu et al., 1989), capture unused solar energy (Singer et al., 2007b), suppress weeds (Blaser et al., 2006), and produce forage for livestock (Blaser et al., 2007).

Producers seeking ways to reduce production costs may consider reduced tillage practices, yet studies evaluating the impact of tillage on crop yields have reported mixed results. Wheat yields have been found to be higher, lower, and unaffected by tillage when comparing IT to NT systems (Lund et al., 1993; Singer et al., 2004; Kumudini et al., 2008). Such inconsistency may limit producer adoption of minimum tillage practices.

Frost-seeding red clover into established winter cereals has been successful under MT and NT practices (Thiessen Martins et al., 2001; Blaser et al., 2006; Singer et al., 2006), yet comparisons of tillage systems within the same study were not performed. Legere et al. (2001) reported mixed tillage effects on interseeded red clover in spring barley (*Hordeum vulgare* L.) with NT producing 16% greater DM than IT in one study year, IT producing 52% greater DM than NT in three years, and three years with no tillage effect. However, the red clover was not frost-seeded in their experiment and they did not report red clover densities. Interactions from spring sown intercrops and winter cereal yield indicate increased complexity when evaluating a winter cereal/legume intercrop.

Cereal grain/legume intercrops have been included in previous crop management studies, yet researchers focused only on main crop yields, N contribution from the legume, or weed suppression, and provided little data about legume establishment or post-harvest productivity (Brandt et al., 1989; Singer and Cox, 1998; Legere et al., 2001). Singer and Cox (1998) evaluated IT and MT in a corn-soybean-wheat/red clover rotation, yet they did not discuss or quantify red clover productivity and cited red clover establishment as a major production challenge in this rotation.

Management practices that increase cereal canopy growth have been reported to limit legume productivity. As cereal seeding rate was increased from 100 to 400 seeds m^{-2}, Blaser et al. (2007) reported similar post-harvest red clover densities, but observed a 30% decrease in DM 40 d after cereal harvest. Measured IPAR for these seeding rates confirmed the differences in canopies as the 300 and 400 seed m^{-2} cereal seeding rate treatments intercepted more IPAR throughout the growing season (Blaser et al. 2006). Blaser et al. (2007)

attributed management practices to the reduced legume DM, but never addressed the possibility that improved cereal growing conditions could result in a more competitive companion crop that may limit legume DM.

Tillage practices and soil amendments alter the quantity of residue on the soil surface. Surface residue may promote soil fissures, minimize surface sealing, reduce evaporation, and ultimately modify microenvironments for frost-seeded red clover germination and seedling establishment (Brady and Weil, 2000). We hypothesized that management practices that enhance the soil microenvironment will increase red clover establishment. Therefore, the objective of this study was to evaluate the effect of IT, MT, and NT tillage systems and the presence of a compost soil amendment on frost-seeded red clover establishment and productivity in winter wheat.

MATERIALS AND METHODS

This winter wheat/red clover intercrop study was conducted from 2005-2008 at the Iowa State University Agronomy and Agricultural Engineering Farm near Ames, IA (42º 00'N, 93º 50'W; elevation 341 m above sea level). The experiment was embedded within a larger study with a history of tillage and compost treatments. The larger experiment was initiated in 1988 as a continuous corn experiment with IT, MT, and NT treatments. In 1997, the entire experiment was planted to soybean and in 1998 a corn-soybean-wheat/clover rotation was initiated with compost/no compost subplot treatments.

The present study focuses solely on the wheat/red clover portion of the rotation. The experimental design was a randomized complete block in a split-plot treatment arrangement with four replicates. Main plots, 22.8 x 26.1 m, were tillage treatments representing IT, MT, and NT management. Tillage treatments were similar during the corn and soybean phases, but differed for winter wheat. Field preparations to produce IT conditions prior to wheat planting consisted of one pass with both a tandem disk and a field cultivator. Moderate tillage seedbed preparation included one pass with a field cultivator and NT conditions were represented by planting wheat directly into soybean stubble. Subplots, 7.6 x 13.0 m, consisted of a fall application of composted beef manure or no compost prior to planting the corn phase of the rotation. Compost was applied based on the P removal rate for corn, soybean, and wheat over the 3-yr rotation (35, 22, and 16 kg P ha^{-1}, respectively). For more information regarding previous experimental procedures see Singer et al. (2004, 2007a).

'Karl 92' hard red winter wheat was planted into Clarion loam (fine-loamy, mixed, superactive, mesic typic Hapludolls) and Canisteo silty clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls) soils. The wheat was planted at 300 PLS m^{-2} on 5 Oct. 2004, 7 Oct. 2005, 6 Oct. 2006, and 28 Sept. 2007 using a tractor-mounted 3.8 m wide John Deere 1520 grain drill (John Deere Co., Moline, IL) with 15 cm row widths. All plots were broadcast fertilized with 45 kg N ha^{-1} in the form of NH_4NO_3 on 4 Apr. 2005, 28 Mar. 2006, 2 Apr. 2007, and 21 Apr. 2008.

The entire subplot was frost-seeded with red clover at a rate of 900 PLS m^{-2} using a tractor mounted drop seeder, except for a 1.2 x 2.4 m microplot area within each subplot, which was covered by plastic to prevent mechanical seeding. This microplot area was frost-seeded by hand immediately following mechanical seeding. Both frost-seeding events occurred on 23 Mar. 2005, 15 Mar. 2006, 26 Mar. 2007, and 24 Mar. 2008. In 2005 and 2006 'Cherokee' red clover was used and in 2007 and 2008, the genetically similar variety 'Southern Belle' (Quesenberry et al., 2005) was used. Southern Belle was developed through a combination of recurrent selection processes using Cherokee as the base population and initial production trials reported similar yields between the two varieties. Light interception and soil moisture data were collected within the 1.2 x 2.4 m microplot area and all red clover and wheat data were collected from two permanent 0.5 m^2 quadrats within each microplot.

Wheat Dry Matter and Yield

A whole plant wheat DM sample was collected when wheat reached maturity [growth stage (GS) 92; Zadoks et al., 1974], just prior to combine harvesting on 7 July 2005, 5 July 2006, and 10 July 2007, 15 July 2008. All wheat plants were cut at the soil surface from one of the two 0.5 m^2 quadrats in each microplot. These samples were dried at 60°C until constant weight and whole sample DM was recorded. The samples were then counted to determine spikes m^{-2} and wheat was threshed. The threshed wheat sample was weighed to determine microplot wheat yield and counted for two 1000-kernel weights. Kernels $spike^{-1}$ were calculated from the total yield, spikes m^{-2}, and 1000-kernel weight data. Whole grain moisture was measured by drying 10 g of grain at 130ºC for 19 h and weighing (ASAE

Method S352.2). Final grain yield was adjusted to 135 g kg^{-1} moisture. The rest of the plot was machine harvested and straw was removed with 1 d of sampling.

Red Clover Density and Biomass

Red clover plant densities were counted approximately every 7 d by counting the plants within two 0.5 m^2 quadrats of each microplot. Seedlings were not counted until the first trifoliolate leaf appeared. Density counts for each season were initiated on 3 May 2005, 21 Apr. 2006, 2 May 2007, and 9 May 2008 and continued until wheat harvest. When assessing red clover densities, the location of plants relative to the wheat row and interrow was documented. Red clover in the wheat row and located within one cm of the wheat row were considered in the row for a total width of five cm. The remaining 10 cm area between rows was considered the interrow. Analysis of plant numbers per location were weighted relative to the area occupied in the 0.5 m^2 quadrat. Plants observed in the row and interrow occupied 0.17 and 0.33 m^2, respectively.

Red clover DM was collected at wheat harvest by using the same 0.5 m^2 quadrat in which the wheat was sampled. Shoot DM was clipped at the soil surface on 7 July 2005, 5 July 2006, 10 July 2007, and 15 July 2008. In 2006-2008, root biomass was also collected by digging the roots of the harvested quadrat to a depth of 25 cm. The red clover from the second quadrat was not harvested at this time. A second red clover sample was collected approximately 40 d after wheat harvest on 16 Aug. 2005, 22 Aug. 2006, 21 Aug. 2007, and 25 Aug. 2008. Red clover plants from the second quadrat in each microplot were excavated and the shoot and root DM was separated. Roots from both harvests were washed to remove all soil and root and shoot samples were oven dried at 70°C until a constant weight was achieved.

Soil Water and PAR Interception

Volumetric soil water content and intercepted photosynthetically active radiation (IPAR) were collected from 2006-2008. Volumetric soil water content of the upper 6 cm of the soil profile was measured with a portable Delta-T Thetaprobe ML2 moisture sensor attached to a Delta-T HH2 handheld data logger (Delta-T Devices Ltd., Cambridge, UK). The measurements were collected approximately every 3-4 d during wheat growth beginning on 19 May 2006, 2 May 2007, and 13 May 2008. Three measurements were collected within the non-trafficked area of each microplot and averaged to determine soil water content in the surface 6 cm.

Seasonal wheat canopy IPAR was determined every 7 d beginning on 19 May 2006, 1 May 2007, and 14 Apr. 2008 using an AccuPAR Linear PAR Ceptometer, Model PAR-80 light measuring instrument (Decagon Devices, Inc., Pullman, WA). Measurements were obtained by placing the ceptometer diagonally across three wheat rows within each microplot. The instrument was positioned below the wheat canopy, but above the red clover plants to measure the quantity of PAR transmitted to the top of the clover canopy. Measurements were collected under full sunlight between 1130 and 1400 h. Percent light transmittance was calculated per subplot by dividing the average of two below canopy PAR readings by one above canopy reading and multiplying by 100.

Weather Data

Weather conditions during the study and long-term climatic data were obtained from the Iowa Environmental Mesonet (IEM, 2008). Daily maximum and minimum air temperatures and rainfall were recorded from a weather station located 1.5 km from the experimental site (Table 1). Between frost-seeding on 26 Mar. 2007 and 3 Apr. 2007, observed average daily air temperature was 13°C and total rainfall was 41 mm. These optimum growing conditions resulted in a high percentage of legume germination. From 4 to 9 Apr. 2007, a severe frost event occurred with average daily temperatures of -3.2°C and average low temperatures of -8.1°C. Damage to both wheat and red clover was observed and the few red clover plants that survived or germinated after the frost event were not adequate for data analysis. Consequently, no red clover data will be presented for 2007.

Statistical Design and Analysis

The experimental design was a randomized complete block in a split-plot treatment arrangement. Statistical analysis was performed using the PROC MIXED procedure of the Statistical Analysis System Version 9.1 (SAS Institute, 2003). Year, tillage, and compost were treated as fixed effects. In all analyses, year was highly significant, so all data are presented by year. When the tillage x amendment interaction was not significant, the interaction was removed from the model and an additive model was assumed. The model used to estimate the location effect on red clover establishment was a split-split-plot. Light transmittance and soil moisture data were analyzed using a repeated measures model with first order autoregressive correlation. A Fisher's protected LSD ($\alpha = 0.05$) was used for all mean separation.

RESULTS AND DISCUSSION

Grain Dry Matter, Yield, and Yield Components

Tillage did not affect whole plant DM at harvest in 2005, 2007, and 2008 (Tables 2 and 3). Similar results were reported by Kumudini et al. (2008) who recorded similar DM production between IT and NT. However, in 2006 wheat grown with IT produced 15% more whole plant DM than NT, while both tillage systems were similar to MT. Soil amendment treatments did not impact whole plant DM in any of the four study years.

Grain yield was influenced by tillage in 2005 and 2007, yet the effect was not consistent. In 2005, IT and MT plots recorded similar yields with a mean of 4.74 Mg ha^{-1} compared with 3.95 Mg ha^{-1} in NT (Table 3). In 2007, the highest grain yields were recorded in NT (2.89 Mg ha^{-1}), which was similar to MT but greater than IT (2.21 Mg ha^{-1}). Moderate tillage and IT yields were not different in 2007. Kumudini et al. (2008) also reported lower wheat yield in two of five site-years in NT compared with MT. The higher NT yields in this study in 2007 may have been influenced by stand reductions in all treatments caused by frost in early April (Table 1). More surface residue in NT may have favorably altered the microenvironment to minimize the frost damage. Similarly to whole plant DM, soil amendment did not affect wheat yield in any year.

Tillage and soil amendment did not influence spikes m^{-2} or 1000-kernel weights in any year (Table 3). Average spikes m^{-2} were 910, 771, 599, and 685 spikes m^{-2} and average 1000-kernel weights were 28, 34, 28, and 30 g for 2005-2008, respectively. Kernels spike^{-1} responded in the same manner as grain yield to tillage system in 2005 and 2007. In 2005, IT produced 19 kernels spike^{-1} compared with 17 in MT and NT. An amendment effect was also observed in 2005, with higher kernels spike^{-1} in the no compost treatment (18 vs. 16). In

2007, NT had greater kernels spike^{-1} than the IT or MT (16 vs. 14). Similar to grain yield, no kernels spike^{-1} effects were observed in 2006 or 2008.

Red Clover Densities and Dry Matter

Red clover densities at wheat harvest in 2005 were similar under NT and MT with a mean of 40 plants m^{-2}, yet IT treatments had lower densities with 28 plants m^{-2} (Table 4). Surface residue with MT and NT systems may have provided more protection for germinating red clover plants or reduced the surface sealing often found after spring rains in tilled soils (Brady and Weil, 2000). By reducing surface sealing more red clover seed may have moved into suitable microenvironments for germination. Furthermore, because grain yields were equal between IT and MT and red clover post-harvest plant counts were similar between MT and NT, we conclude that the decrease in red clover counts in IT was not attributable to greater companion crop competition, but rather, less favorable soil microenvironment. Red clover densities at harvest in 2006 and 2008 averaged 43 and 104 plants m^{-2}, but were not influenced by tillage or compost treatments.

Red clover shoot DM at wheat harvest was not affected by tillage in 2005, in spite of the lower plants counts in IT (Table 4). A soil amendment treatment effect was observed in 2005 with 73% more shoot DM produced with the no compost treatment. Previous soil management practices for the crop rotation included application of compost prior to corn and soybean planting each year (Singer et al., 2004). The 2005 wheat/red clover phase of the rotation had two compost applications in the last three years compared with the 2006 and 2008 years, which only had one. No compost treatment effects were observed for red clover DM at wheat harvest in 2006 or 2008. Red clover root DM at wheat harvest averaged 0.3 and 5.1 g m^{-2} in 2006 and 2008, respectively, but was not affected by tillage or amendment treatments in either year. No tillage x amendment interactions were detected for red clover densities or DM at wheat harvest.

Red clover plant density 40 d after wheat harvest was only affected by amendment treatment in 2005. The no compost treatment averaged 63 plants m^{-2} compared with 37 plants m^{-2} with compost. The average density across the 2005 tillage treatments was 50 plants m^{-2}, 14 plants higher than at wheat harvest. This increase in plants from wheat harvest to 40 d after harvest was similar to observations by Blaser et al. (2007). They reported an increase from post-harvest densities to the following spring and cited greater light transmittance and late summer rainfall as potential factors influencing hard seed or improving microenvironments for late season germination of frost-seeded red clover. Red clover 40 d plant densities averaged 42 and 94 plants m^{-2} in 2006 and 2008, averaged across tillage and compost treatments.

Shoot DM measured 40 d after wheat harvest in 2005 was 164 g DM m^{-2} in the no compost treatment compared with 51 g DM m^{-2} with compost (Table 4). Greater shoot DM corresponded directly to greater plant numbers and resulted in approximately double the DM per plant (DM/plant density). Shoot DM in 2006 averaged 164 g DM m^{-2}, but as with 40 d densities, were not impacted by treatment. In 2008, a tillage x amendment interaction was observed for 40 d shoot DM when compost increased DM in IT 38% while NT and MT DM decreased 27% compared with no compost. Legere et al. (2001) did not observe a tillage effect on red clover DM in three of seven years using spring barley, but did record greater DM production with NT in one year and three years with IT. Root DM collected in 2006 and 2008 averaged 7.9 and 13.7 g m^{-2}, respectively, and produced 25% more DM in the no compost compared with the compost treatment in 2008.

Red clover taproot lengths were measured in 2008 (data not shown). At wheat harvest, the average taproot length was 9.8 cm, yet no treatment effects were observed. Red clover plants at the 40 d sampling had 8% longer taproots under NT (12.8 cm) than MT and IT.

Tillage effects for wheat yield and red clover DM resulted in very few significant effects in this study. Although not significant at $p < 0.05$, MT produced similar or greater wheat yields and red clover DM across all years compared to NT and IT (Tables 2, 3 and 4). This consistent response suggests that optimum soil conditions that support both wheat and red clover productivity, without limiting yield of either crop, may be achieved with MT.

Spatial Location of Red Clover Plants

Visual observations from previous intercropping studies indicated that frost-seeded red clover produced more plants in or near to the cereal grain row compared with the interrow area. A location effect was observed early in the season of 2005, but did not persist. In 2006 and 2008, there was a significant location effect with more plants observed in the row compared with the interrow. An average of 10 and 45 plants m^{-2} were observed for the row and interrow at wheat harvest in 2006 (data not shown). An amendment x location interaction was observed in 2006, which was a result of more plants in the row of the no compost treatment compared with the row of the compost treatment (25 vs. 35 plants m^{-2}), while both interrow plant densities were similar. In 2008, an average of 45 and 67 plants m^{-2} were observed for the row and interrow. A tillage x location interaction was observed in 2008 and was caused by lower densities observed in the row of NT compared with the interrow (34 vs. 67 plants m^{-2}), while the densities of both locations were similar in MT and IT (51 and 56 plants m^{-2}). More uniformly distributed plants or slightly lower densities in the row of NT may have been caused by limited water movement and greater water infiltration caused by surface residue. It is possible that more plants in the row position is the result of physical factors. Press wheels on the grain drill cause depressions in the soil that may lead to more overland water flow, possibly carrying more broadcasted seed to that location. Also, the presence of winter wheat at frost-seeding allows for a more protected microenvironment for germination and possibly more soil fissures for seeds to achieve seed-to-soil contact for germination. This microenvironment may also protect young seedlings during early growth and funnel future rainfall into the row.

Under normal production environments, plant location may not be as critical as plant density and productivity. Yet producers seeding winter cereals at row widths greater than 15 cm may produce inconsistent legume stands and cause larger portions of the field to have a lower overall stand densities and productivity. Sparse stands may also impact the distribution of legume N from decaying red clover plants and the suppression of weeds.

Resource Competition

Wheat canopy IPAR was measured from 2006-2008. No consistent tillage or amendment effects were observed, so presented data are averaged across these factors (Fig. 1). Differences among tillage treatments were only observed on three dates in 2007. On 1 May, IT and MT wheat recorded 11% more IPAR than NT. On 21 May and 20 June, NT wheat IPAR was an average of 9% less than IT, while both tillage systems were similar to MT at those dates. No other significant tillage effects were observed, yet general trends were still noted as seasonal average IPAR ranked in order with IT > MT > NT. However, these non-significant differences only varied from 1 to 4% at different point measurements throughout the season.

A significant amendment effect was observed for canopy IPAR in 2006. The compost treatment averaged 4-7% greater IPAR throughout the season with significant differences recorded on 19 May and 13 and 26 June and an average of 7% more IPAR by wheat in the compost treatment on those dates. No significant differences were observed for 2007 or 2008 as average seasonal trends resulted in only 2 and 2.5% more IPAR with compost.

Soil moisture differences were only observed in 2008 tillage treatments. On 17, 20, and 23 June, more soil moisture was measured in IT (0.246 m^3 m^{-3}) compared with MT and NT (0.199 m^3 m^{-3}). On 2 July, more soil moisture was observed in IT (0.257 m^3 m^{-3}) than NT (0.212 m^3 m^{-3}), on 7 July more soil moisture was observed in IT (0.204 m^3 m^{-3}) than MT (0.171 m^3 m^{-3}), and on 9 July more soil moisture was observed in IT (0.355 m^3 m^{-3}) than NT (0.321 m^3 m^{-3}). Even though soil moisture differences were observed in 2008, the potential effect on red clover densities and DM was not observed at grain harvest or 40 d after harvest (Table 4).

CONCLUSIONS

Tillage systems inconsistently affected wheat grain yield. Tillage effect on red clover densities may be present at wheat harvest but is diminished 40 d later and does not impact red clover shoot DM. Moderate tillage resulted in more consistent yields of wheat and red clover in all years. The application of compost reduced red clover shoot DM. Although statistical differences were not detected, compost amended wheat produced higher grain yields in two of three red clover production years. The impact of compost on grain yields may have also resulted in a more competitive companion crop that limited red clover DM. More frost-seeded red clover plants established in the grain row than the interrow and should be a consideration for producers using wide row spacing for cereal grain production. Producers should achieve similar red clover densities and DM using this intercrop in reduced tillage systems. However, they must evaluate the tradeoff between the positive effect of compost on corn and soybean in the rotation and the potentially negative residual effect of compost on red clover DM production.

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LIST OF FIGURES

Table 1. Average monthly air temperature and rainfall near Ames, IA from 2005-08†. Thirty-year averages (30-yr) were computed from data collected approximately 1.5 km from the experimental site from 1975-2004.

	Air temperature					Rainfall				
Month	2005	2006	2007	2008	30-yr	2005	2006	2007	2008	30-yr
	°C					mm				
March	3.0	3.3	6.0	1.0	2.8	35	74	81	71	53
April	12.8	13.1	8.7	8.4	10.3	82	109	153	130	93
May	15.5	17.0	19.0	15.2	16.5	111	55	169	216	112
June	23.0	22.1	22.2	21.2	21.4	124	21	52	271	119
July	24.1	24.4	23.8	23.2	23.5	104	141	75	234	112
August	22.1	22.6	24.1	21.5	22.1	172	156	200	53	120

† NWS COOP site Ames 8WSW.

Table 2. Tillage (T), amendment (A) and T x A interaction *P* - values for grain and red clover analyses from 2005-2008.

	Grain					Red clover					
	WP DM†	Grain yield	Spikes m^{-2}	Kernels $spike^{-1}$	TKW‡	Harvest density	Harvest shoot DM§	Harvest root DM	40 d density	40 d shoot DM	40 d root DM
	P > F										
	2005										
T	0.1186	0.0340	0.0812	0.0037	0.1541	0.0149	0.2081	-¶	0.4387	0.0998	-
A	0.1985	0.3508	0.0941	0.0163	0.1307	0.0918	0.0091	-	0.0026	0.0010	-
T x A	0.9442	0.7228	0.4543	0.9864	0.9241	0.2244	0.6826	-	0.1501	0.5222	-
	2006										
T	0.0402	0.1100	0.0775	0.5669	0.2019	0.7575	0.9527	0.8008	0.8898	0.6654	0.6333
A	0.2768	0.7017	0.1579	0.3094	0.6447	0.1680	0.1326	0.1509	0.0978	0.6675	0.3206
T x A	0.8543	0.4483	0.5204	0.9545	0.8108	0.2016	0.1061	0.0636	0.3804	0.8084	0.7222
	2007										
T	0.1764	0.0382	0.4449	0.0368	0.4567	-#	-	-	-	-	-
A	0.1405	0.4280	0.6131	0.4694	0.3448	-	-	-	-	-	-
T x A	0.3316	0.2271	0.8144	0.7004	0.0515	-	-	-	-	-	-
	2008										
T	0.5763	0.8141	0.6922	0.8460	0.5051	0.5683	0.2531	0.2248	0.0646	0.1811	0.0840
A	0.2675	0.6339	0.9498	0.4698	0.7378	0.5081	0.7272	0.6119	0.1795	0.6158	0.0252
T x A	0.9049	0.7754	0.7178	0.3883	0.2899	0.8329	0.5784	0.4869	0.8025	0.0036	0.3232

† WP DM, whole plant dry matter.

‡ TKW, thousand kernel weight.

§ DM, dry matter

¶ No root data was collected in 2005

No red clover data were presented in 2007 because frost damaged stands were not adequate for data analysis.

Table 3. 'Karl 92' hard red winter wheat whole plant dry matter (WP DM), grain yield, and yield components for intensive tillage (IT), moderate tillage (MT), or no-tillage (NT), and compost (C) amendment or no compost (NC) treatments during 2005-2008 near Ames, IA.

	WP DM	Grain yield	Spikes m^{-2}	Kernels spike^{-1}	TKW†
Factor	g m^{-2}	Mg ha^{-1}	no.	no.	g
			2005		
Tillage					
IT	1277	4.67a‡	875	19a	27.7
MT	1290	4.81a	983	17b	28.7
NT	1152	3.95b	872	16b	28.1
Amendment					
C	1278	4.35	948	16b	27.9
NC	1202	4.60	872	18a	28.5
			2006		
Tillage					
IT	1262a	5.28	833	19	33.7
MT	1189ab	4.92	760	19	34.1
NT	1071b	4.74	720	20	33.1
Amendment					
C	1205	5.02	799	19	33.5
NC	1142	4.94	743	20	33.7
			2007		
Tillage					
IT	600	2.21b	568	14b	27.3
MT	635	2.50ab	611	14b	28.7
NT	698	2.89a	618	16a	28.5
Amendment					
C	676	2.61	608	15	27.7
NC	612	2.45	590	15	28.6
			2008		
Tillage					
IT	880	3.02	680	15	29.8
MT	862	3.14	713	14	30.8
NT	803	2.95	661	15	30.3
Amendment					
C	884	3.09	683	15	30.4
NC	813	2.98	686	14	30.1

† TKW, thousand kernel weight.

‡ Means followed by the same letter within the same column and treatment factor are not significantly different using a Fisher's protected LSD at $P < 0.05$.

Table 4. Red clover plant density, shoot and root dry matter (DM) at wheat harvest and 40 d after harvest for intensive tillage (IT), moderate tillage (MT), or no-tillage (NT), and compost (C) amendment or no compost (NC) treatments during 2005-2006 and 2008 near Ames, IA.

Factor	Harvest density plants m^{-2}	Harvest shoot DM g m^{-2}	Harvest root DM g m^{-2}	40 d density plants m^{-2}	40 d shoot DM g m^{-2}	40 d root DM g m^{-2}
			2005			
Tillage						
IT	28b†	1.9	-	43	64	-
MT	39a	4.4	-	53	114	-
NT	40a	5.1	-	54	144	-
Amendment						
C	33	1.6b	-	37b	51b	-
NC	39	6.0a	-	63a	164a	-
			2006			
Tillage						
IT	38	1.4	0.2	42	90	6.8
MT	46	1.5	0.3	44	113	8.8
NT	44	1.5	0.3	40	92	8.0
Amendment						
C	36	1.1	0.2	36	93	7.0
NC	50	1.8	0.3	49	103	8.8
			2008			
Tillage						
IT	100	38.7	4.4	102	158	14.2
MT	112	64.6	6.7	106	189	15.9
NT	101	41.3	4.3	75	144	11.2
Amendment						
C	101	45.8	4.8	89	159	11.8b
NC	108	50.6	5.5	102	169	15.7a

† Means followed by the same letter within the same column and treatment factor are not significantly different using a Fisher's protected LSD at $P < 0.05$.

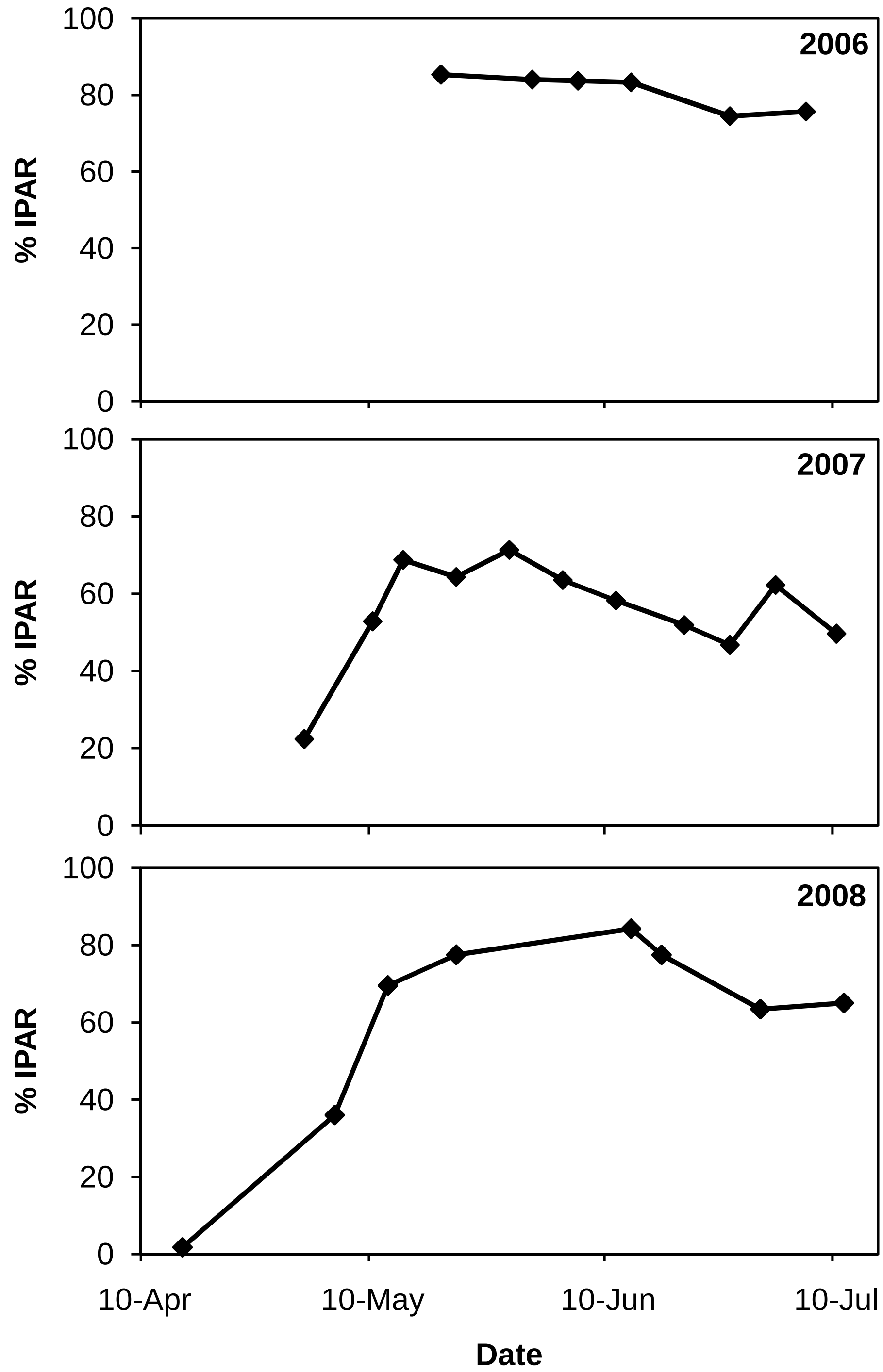

Figure 1. ‘Karl 92’ hard red winter wheat percent intercepted photosynthetically active radiation (IPAR) averaged across Intensive tillage, moderate tillage, and no-tillage and the presence or absence of compost amendment near Ames, IA from 2006-2008.

Chapter 4: Predicting Interseeded Legume Establishment in Winter Cereals

A paper to be submitted to *Field Crops Research*

Brock C. Blaser,* Jeremy W. Singer, Lance R. Gibson, Garritt L. Page,
Matt Liebman, and Robert P. Anex

ABSTRACT

Accurately predicting interseeded legume plant density after cereal grain harvest provides important management information to producers using intercropping systems. Surface soil water content and intercepted photosynthetically active radiation (IPAR) were assumed to be the dominant resources affecting legume survival. Linear models to predict legume densities were developed using cereal leaf area index (LAI), IPAR, cereal species and legume origin. Soil water content was assumed not to contribute to legume mortality because soil water content did not exceed the permanent wilting point for an extended duration during the two growing seasons when data were collected to develop the models. When maximum cereal LAI > 4.1 and IPAR exceeded 90%, the models predicted post-harvest legume densities within five plants m^{-2} or 2 to 11% of observed densities. When maximum cereal LAI < 4.1 and IPAR remained below 90%, estimates were less accurate, predicting densities of 16 and 24 plants m^{-2} or 16 and 21 % less than observed. Model validation using independent data from experiments with different cultural practices in different years was less robust with an average prediction error of 30%. Possible sources of error include the use of an IPAR function to estimate IPAR using a long-term solar radiation record, potential for soil water limitations in validation years, and the use of an average parameter (slope) rather than specific parameters selected using an objective selection criterion. Further model improvements are likely by expanding the model to include other parameters and using a larger model development dataset.

INTRODUCTION

Incorporation of winter cereal grains into the North Central USA corn (*Zea mays* L.)/soybean [*Glycine max* (L.) Merr.] rotation could improve yields of subsequent crops (Crookston et al., 1991), reduce erosion (Zhu et al., 1989), and serve as a companion crop for small seeded legume establishment (Blaser et al., 2006; Singer et al., 2006). Forage legume intercrops can provide high quality feed for livestock (Blaser et al., 2007), suppress weeds (Mutch et al., 2003; Blaser et al., 2006), and provide nitrogen for subsequent crops (Hesterman et al., 1992). Winter cereal grain/legume intercrops managed for maximum grain and legume production have been successful in the North Central USA (Hesterman et al., 1992; Mutch et al., 2003; Blaser et al., 2006; Singer et al., 2006). However, winter cereal species effects on the interseeded legume have been reported by Blaser et al. (2006), who found that triticale (X *Triticosecale* Wittmack) lowered red clover (*Trifolium pratense* L.) post-harvest plant density 18% compared with wheat (*Triticum aestivum* L.) in one of two years. Additionally, Blaser et al. (2006) reported higher red clover densities in a year when transmitted radiation to the interseeded red clover canopy was higher, although no differences in winter cereal were observed.

Light transmittance through the cereal canopy to the legume is a critical factor influencing legume survival and productivity (Klebesadel and Smith, 1959). Results from photosynthesis studies estimate the red clover light compensation point to be 3 to 6% of full sunlight (McKee, 1962). A review on alfalfa (*Medicago sativa* L.) physiology suggests the light compensation point for alfalfa is between 5 and 13% (McKee, 1962; Heichel et al., 1988). The light compensation point represents the minimum quantity of light necessary for plant maintenance. Winter cereal grain canopies from previous intercropping studies intercepted a maximum of 71 to 93% PAR at maximum canopy development (Klebesadel and Smith, 1959; Thiessen Martens et al., 2001; Blaser et al., 2006), but percent light interception and the duration of maximum levels varied among species. Additionally, these studies only contained single varieties of wheat, rye (*Secale cereale* L.), or triticale, and conclusions about the influence of light interception or the cereal grain on legume establishment are limited to the varieties used in the respective experiments.

Legume response to intercropping has also been shown to vary. Singer et al. (2006) reported post-harvest red clover densities in Iowa of 176 to 266 in one year and 17 to 42 plants m^{-2} in a second year using red clover varieties from different origins. These differences represent a 51 and 147% range in densities over two years among 15 cultivars. Klebesadel and Smith (1959) reported an average of 45 and 91 plants m^{-2} for red clover and alfalfa, respectively, when interseeded with winter wheat and rye. These results demonstrate the variability of legume selection within and across legume species and winter cereal species on post-harvest legume plant number. Plant number is related to dry matter (DM) production in red clover. Blaser et al. (2006) reported that maximum red clover DM yield was obtained with plant counts greater than 120 plants m^{-2}. Singer et al. (2006) reported that the relationship between red clover plant number and shoot DM at cereal grain harvest was not significant in a year with high red clover plant counts (176 to 266 plants m^{-2}) and highly significant in a year with low red clover plant counts (17 to 42 plants m^{-2} in Iowa and 28 to 68 plants m^{-2} in Wisconsin). Consequently, predicting the legume stand count before cereal harvest can provide important management information to assist producers with management decisions during the latter half of the growing season.

A predictive tool for producers must be simple to use and not require onerous data input. Because we hypothesized that legume mortality was driven mainly by competition for light and water, our goal was to quantify these resources over time in a interseeding experiment using multiple winter cereals and legumes. The specific objectives of this research were to 1) identify abiotic factors contributing to legume mortality across winter cereal and legume species, 2) develop models that accurately predicted post-harvest legume plant counts using the experimental data, and 3) validate the models using independent data from other interseeding studies to evaluate model precision and robustness.

MATERIALS AND METHODS

Field Experiment – Model Development

A winter cereal grain/legume intercrop study for model development was conducted from 2005-2006 at the Iowa State University Agronomy and Agricultural Engineering Farm near Ames, IA (42º 00’N, 93º 50’W; elevation 341 m above sea level). Treatments were arranged as a split-block with four replicates with cereal grain varieties as main plots and legume as subplots.

‘Décor’, ‘Lamberto’, and ‘NE426GT’ winter triticale varieties and ‘Ernie’ and ‘Kaskaskia’ soft red and ‘Goodstreak’ hard red winter wheat varieties were planted no-till into recently harvested soybean fields with Nicollet loam (fine-loamy, mixed, superactive, mesic aquic hapudolls) soil in 2005 and Webster loam (fine-loamy, mixed, superactive, mesic typic endoaquolls) soil in 2006. The cereal grains were planted at 300 PLS m^{-2} on 5 Oct. 2004 and 7 Oct. 2005 using a tractor-mounted 3.8 m wide John Deere 1520 grain drill (John Deere Co., Moline, IL) with 15 cm row widths. The planted area for each cereal grain variety was 7.6 x 30 m. All six cereal grain varieties were machine harvested on 13 July 2005 and 17 July 2006 and the straw was baled and removed the same day.

In 2005, ‘Cherokee’ red clover was frost-seeded in subplots within each cereal grain variety plot on 23 March. ‘Marathon’ red clover and ‘Mycogen 4375LH’ alfalfa were frost-seeded on 29 March. In 2006 all three legumes were frost-seeded on 15 March. Legumes were seeded at 900 PLS m^{-2} using a tractor-mounted, 3.66 m wide Gandy Model #1012T-TBM drop spreader (Gandy Co., Owatonna, MN). Cherokee and Marathon were selected for their high DM production and diversity in origin, below 38° North (Southern varieties) and Wisconsin or Northern varieties, respectively (Singer et al., 2006). Mycogen 4375LH alfalfa (hereafter referred to as alfalfa), a commercially available and locally adapted variety with a fall dormancy rating of 3.8, was included to evaluate frost-seeded alfalfa establishment success under winter cereals managed for grain. A fourth subplot within each cereal grain variety was a check plot with no legume seeded. Each subplot area occupied 7.6 x 7.3 m. All plots were broadcast fertilized with 45 kg N ha^{-1} in the form of NH_4NO_3 on 4 Apr. 2005 and 29 Mar. 2006. In 2006, 60 kg P ha^{-1} in the form of P_2O_5 was also applied on 29 March.

Cereal Grain Canopy Measurements

Cereal canopy IPAR was measured every 7 d using an AccuPAR Linear PAR Ceptometer, Model PAR-80 (Decagon Devices, Pullman, WA). Measurements were obtained by placing the ceptometer diagonally across three grain rows, but above the legume seedlings to measure the quantity of PAR transmitted to the legume canopy. Measurements were collected under full sunlight between 1130 and 1400 h. Percent IPAR was calculated per subplot by dividing the average of two below canopy readings by one above canopy (incident) reading, multiplying by 100, and then subtracting from 100. Because percent IPAR was collected as a point measurement, average daily IPAR was estimated via linear interpolation.

Cereal grain canopy LAI was measured every 18 d beginning at jointing (growth stage 30; Zadoks et al., 1974) through grain harvest. These measurements were initiated on 21 Apr. 2005 and 24 Apr. 2006. Data were obtained using the LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE) by placing the light sensor in the interrow of two untrafficked grain rows. One above (incident) and two below canopy measurements were taken in each subplot.

Volumetric soil water content of the upper 6 cm of the soil profile was measured with a portable Delta-T Thetaprobe ML2 moisture sensor attached to a Delta-T HH2 handheld data logger (Delta-T Devices Ltd., Cambridge, UK). The measurements were collected approximately every 7 d during cereal growth. Three measurements were collected within the non-trafficked area of each subplot and averaged to determine soil water content in the surface 6 cm.

Legume Densities

Red clover and alfalfa plant densities were measured weekly by counting the plants in one 0.5 m^2 permanent quadrat per subplot. Seedlings were counted after the first trifoliolate leaf appeared, beginning in late April or early May of each year. Data were used for model development after the maximum number of plants was observed, which occurred May 10 each season.

Weather and Solar Radiation Data

Weather conditions and solar radiation during the study and long-term climatic and radiation data were obtained from the Iowa Environmental Mesonet (IEM, 2008). Average daily maximum and minimum air temperatures, monthly rainfall (Table 1), and daily total solar radiation were recorded from a weather station located 0.5 km from the model development experimental site. Daily solar radiation data were the sum of average measured hourly radiation per d during the growing season (15 April to 15 July) of each model development year. Radiation was measured using a LI-COR pyranometer, model LI200X (LI-COR Inc., Lincoln, NE), converted from Langley's (cal m^{-2}) to moles of IPAR per d (mol d^{-1}), and was assumed equal to 0.5 times the daily incident solar radiation (Szeicz, 1974).

Statistical Design and Analysis

The experimental design was a randomized complete block in a split block treatment arrangement. Analysis of variance (ANOVA) and regressions were performed using PROC MIXED of the Statistical Analysis System Version 9.1 (SAS Institute, Cary, NC). Year, variety, and legume were all considered fixed effects. Soil moisture and IPAR data were analyzed using a repeated measures model.

RESULTS AND DISCUSSION

Model Development

Model development focused on seasonal legume densities and the impact of resource competition on legume mortality. The two dominant resources that were hypothesized to be affecting legume mortality were soil water content and light. Weekly soil moisture measurements in the surface 6 cm of soil, the critical depth for seedling root growth during establishment, were analyzed for each cereal grain and legume subplot, including the no legume check plot. In both model development years, no soil moisture effects were observed for cereal variety or legume, confirming that in the two years of this study, soil moisture was not influenced by cereal variety or the presence of a legume intercrop (Fig. 1).

The calculated permanent wilting point (PWP) for the soils in this experiment was 0.147 m^3 m^{-3} (S.D. Logsdon, personal communication, 2008). Only one measurement in either year, observed on 15 June 2006, fell below this critical value (Fig. 1). Blaser et al. (2006) reported soil moisture as low as 0.12 m^3 m^{-3} for an unspecified time, but concluded that available soil moisture could decrease to low levels for short durations without increasing legume mortality. Because no effect of cereal variety or legume was observed for soil moisture and only one soil moisture reading across the two years was below the PWP, we concluded that soil moisture was not a factor influencing legume mortality during the model development years.

Weekly IPAR observations resulted in a cereal variety effect in both years and corresponded closely with measured LAI and final legume densities (Chapter 1). For example, Lamberto triticale recorded the highest IPAR (Fig. 2), produced near maximum LAI, and had the lowest legume densities compared to the other five cereal varieties in both study years (Chapter 1). The effect of light interception on legume densities and reports from previous research (Flanagan and Washko, 1950; Klebesadel and Smith, 1959) supported our hypothesis that IPAR directly influenced legume mortality.

A cumulative IPAR model was developed to integrate the seasonal influence of light interception on legume survival under the cereal canopy. Cumulative IPAR was calculated by multiplying measured daily percent IPAR (Fig. 2) by 50% of observed daily total solar radiation (Szeicz, 1974). These daily values were summed, beginning 15 April until grain harvest. The summed IPAR value is the independent variable for the linear equations developed to predict post-harvest density.

To assess differences among cereal varietal effects on legume densities, the seasonal legume plant densities under each cereal variety were regressed with their respective cumulative IPAR. These regressions were performed for each subplot and resulting intercepts and slopes were subjected to an ANOVA. Intercepts were similar among years, but significant cereal variety and legume effects were observed (Table 2). Marathon red clover and alfalfa intercept means were similar to each other, but different from Cherokee red clover. This ANOVA observation was confirmed by testing for differences in linear combinations of the parameter means and resulted in the calculation of the mean of the Marathon and alfalfa intercepts. The intercept of Lamberto triticale was significantly lower than the other five cereal varieties. Additional linear combination tests comparing the intercept mean of Lamberto with the mean of Décor, NE426GT, Ernie, Goodstreak, and Kaskaskia confirmed the grouping and a mean of the five varieties was computed (Table 2).

A year effect was observed for the slopes, so further analyses were performed by year. In 2005, both cereal variety and legume main effects were significant (Table 2). Similar to the intercept analyses, Cherokee was different from Marathon and alfalfa, and Lamberto was different from the other five cereal varieties. Differences in linear combination analyses confirmed the respective grouping and averaging of the slopes in 2005

(Table 2). The 2006 slopes were similar across cereal variety and legume, so one mean slope was calculated for all potential equations.

Intercept and slope analyses resulted in one intercept for Cherokee and two possible intercepts for Marathon and alfalfa. As the slopes were specific to model development year and cereal variety, it was necessary to identify a slope selection factor independent of year, but still associated with cereal variety. The cereal variety slopes directly reflected the maximum cereal LAI measurements (Chapter 1). In 2005, Décor, NE426GT, Ernie, Goodstreak, and Kaskaskia produced maximum LAI values between 4.1 and 5.7 while Lamberto had a maximum value of 6.2. In 2006, maximum LAI values for all six cereal varieties were below 4.1. This relationship allows the cereal LAI to be the initial slope selection factor when associated with a specific legume (Table 3).

When the legume is Cherokee red clover the intercept is 97.3. The slope is -0.0049 (CH1) if the cereal LAI $\leq$ 4.1 or -0.0209 (CH2) if the cereal LAI > 4.1. When the legume is Marathon red clover or alfalfa then three intercepts and two slopes are possible. When the cereal LAI $\leq$ 4.1, the slope is -0.0049; when the LAI > 4.1 and < 5.7, the slope is -0.045 (MA3); and when the LAI $\geq$ 5.7 the slope is -0.0194 (MA4). To select the most appropriate intercept for Marathon red clover or alfalfa when cereal LAI $\leq$ 4.1, an initial legume stand density assessment is required. Based on a spring density count, the model user must select one of two contrasting intercept values. The intercepts 105.7 and 194.5 were the result of analyses in 2005 and 2006, respectively. Therefore, if spring density counts, recommended to be assessed after 10 May, are closer to 100 plants m^{-2}, we recommend using the intercept of 105.7 (MA1). Spring density counts closer to 200 plants m^{-2} would then suggest the selection of the larger intercept value, 194.5 (MA2) (Table 3).

Predicted vs. observed graphs for the six possible models demonstrate the accuracy of the models when predicting the post-harvest densities relative to a 1:1 line (Fig. 3). Model predictions in 2005 were highly accurate with root mean square errors (RMSE) ranging from six to 11 for the three models. All three models predicted post-harvest densities within five plants m^{-2} or fewer than observed plant densities or between two and 11% (Table 3; Fig. 3 A, B, C). The higher cereal LAI in 2005 caused an increase in IPAR and a linear decline in legume densities (Chapter 1). In the case of Lamberto, IPAR was greater than 94% from 10

May to 6 June (Fig. 2). This duration of low PAR for the legumes may have caused legume mortality as light compensation points for both red clover and alfalfa were exceeded (McKee, 1962; Heichel et al., 1988).

The 2006 model predictions were more variable with RMSE ranging from 12 to 19. The post-harvest density predictions for the three models ranged from 3 to 24 plants m^{-2} from the observed (Fig. 3 D,E,F). The MA3 model predicted only three plants m^{-2} or 2% more than observed while the CH1 and MA1 models under predicted the densities by 16 and 24 plants m^{-2} or 16 and 21%. The greater variability in the latter two models was most likely attributed to the variability in seasonal density counts in 2006 and the lack of legume mortality that was observed because of lower cereal LAI (Chapter 1) and IPAR values never falling below the light compensation points for either red clover or alfalfa (Fig. 2). The lower LAI in 2006 resulted in very small slope parameters for the 2006 models. Additionally, the initial densities in 2006 were much higher, which could be attributed to the warmer air temperatures and above normal rainfall during establishment in March and April (Table 1). However, factors influencing initial spring densities are not well understood and may contribute to the interaction of biotic and abiotic factors.

In order to select the most accurate model, it is necessary to know the legume origin, cereal LAI, and in some cases, the spring legume plant density. When selection inputs are not available, or do not meet the selection criteria, an average model was developed with more general predictions, using averaged parameters. The intercepts remain the same, as analyses confirmed their application across the two model development years, but the slopes of the two years were averaged to provide a simpler, but less accurate, estimation. If the legume is Cherokee red clover, the intercept is still 97.3 and the new slope is -0.0087. If the legume is Marathon red clover or alfalfa, then the model user must still know the spring stand density. When the spring density is closer to 100 plants m^{-2}, the intercept will be 105.7 and the new slope will be -0.0104. When the initial density is closer to 200 plants m^{-2}, then the intercept is 194.5 and the new slope is -0.0279 (Table 3).

As expected, when averaging the slopes over years and treatments, the prediction accuracy of the model decreases. An attempt to compare the model development years with their slopes (Fig. 3) to the average slopes demonstrated this expectation (Fig. 4). In all cases, the RMSE was higher when using the average slope and the post-harvest predictions were higher and lower for the 2005 and 2006 model development data, respectively. In five of the six models, the post-harvest predictions were off between 37 to 56% (Fig.4 A, B, C, D, F). Only the MA1 model (using the average slope) predicted a post-harvest density similar to the observed (within three plants m^{-2}). However, this same model, when applying the original slope, also predicted the post-harvest density within three plants m^{-2} (Fig. 4 E).

Model Validation

To apply these models beyond the development years when IPAR may not be available, a quadratic equation was fit to six years of average IPAR (Fig. 5). The equation was fit using R statistical software (R Foundation for Statistical Computing, Vienna, Austria) and fitting the best curve with an $R^2 = 0.73$. The six years of IPAR data were obtained from a previous intercropping study (Blaser et al., 2006), the model development experiment from 2005-2007, and the model validation experiment in 2008. The curve represents the average daily IPAR for central Iowa over a range of growing seasons and winter triticale and wheat varieties. By solving the quadratic equation for day of the year, the model user will obtain average IPAR data to calculate the daily cumulative IPAR needed to multiply by the daily solar radiation.

Daily total solar radiation for the model validation years was an average of 19 yr of measured solar radiation from 1986 to 2004 in central Iowa. The data averaged 30 and 34 mol d^{-1} for April and May, increased rapidly during the first 15 d of June with average of 40 mol d^{-1} and continued to rise to an average of 45 mol d^{-1} for the last 15 d of June (data not shown). Average radiation began to decrease in the first 15 d of July with 43 mol d^{-1}. Maximum values were observed during the last two weeks of June, corresponding to maximum day lengths during summer solstice. After multiplying by the daily cumulative IPAR the total mol using these average data was 2353 for the period 15 April to 15 July. This number is the dependent variable when solving the linear models in non-development years.

The main validation data were obtained from an intercropping study < 1.0 km from the model development experimental site for 2005, 2006, and 2008. ‘Karl 92’ hard red winter wheat was used in this study and has been reported to produce similar LAI values as

Kaskaskia, Ernie, and NE426GT (Iutzi, 2006) and Cherokee and genetically similar 'Southern Belle' (Quesenberry et al., 2005) red clovers were used. Leaf area index was not measured in this validation experiment, so in order to improve the accuracy in model selection it was assumed that LAI measured for similar varieties in neighboring studies during the same years (< 1.0 km away from the experimental site) would be similar to the LAI produced by Karl 92. In 2005 and 2006, the reported LAI was > 4.1 and < 4.1 for wheat varieties similar to Karl 92, respectively (Chapter 1; Singer et al., 2007b). These 2005 and 2006 LAI values invoked the slope selection of -0.0209 and -0.0049, respectively, and were combined with the intercept of 97.3. The 2008 model validation year did not have LAI measurements, nor were neighboring studies available for comparison. Therefore, the average slope of -0.0087 and intercept of 97.3 were used to predict 2008 post-harvest densities. All of the validation models used the 6 yr IPAR data (Fig. 5) and 19 yr average solar radiation to produce the dependent variable.

The 2005 and 2006 validation years were over predicted by 23 and 55% while the 2008 validation year was under predicted by 29% (Table 4; Fig. 6). The RMSE of all three years were similar to or slightly higher than the average slopes applied to the model development data. To further test the models, predictions were compared to post-harvest densities of two previous intercropping studies using Kaskaskia winter wheat and 'Presto' winter triticale (Blaser et al., 2006; Singer et al., 2007b). The 6 yr IPAR and 19 yr average radiation data were used to estimate the seasonal cumulative IPAR for the two studies and when LAI measurements were made, specific model slopes were selected.

In 2004 and 2006, Kaskaskia recorded a maximum LAI < 4.1 (slope = -0.0049) and Presto had a maximum LAI > 4.1 (slope = -0.0209) (Table 4; Singer et al., 2007b). Blaser et al. (2006) did not report LAI, so the average slope of -0.0087 was combined with the Cherokee red clover intercept of 97.3. Prediction results varied similarly to the other validation data (Table 4; Fig. 7). The prediction values ranged from six to 43 plants m^{-2} different than observed data in Singer et al. (2007) and under predicted 39 and 48 plants m^{-2} from observed data in Blaser et al. (2006). The more precise predictions reflected models with specific slopes with an average prediction error of 30% compared to the average slope over and under estimating by as much as 58 and 38%, respectively (Table 4).

Prediction accuracy for legume densities is important for post-harvest management decisions. However, abiotic and biotic factors interact with plant density after cereal harvest and significantly affect season DM production. Singer et al. (2006) reported mean red clover post-harvest densities of 229 and 30 plants m^{-2} for two different study years and mean DM production of 497 and 566 g m^{-2} for the same two years. Dry matter production in the first year was limited by below normal rainfall late in the season. When rainfall is below the long-term average after cereal harvest, legumes may not produce maximum DM, independent of density. Likewise, when normal or above normal rainfall is received, individual plant DM production may compensate for lower legume density. Even though soil moisture content was not a factor influencing legume densities in the model development years, it influences legume DM production and should be considered in future model development.

In years when LAI measurements allow improved slope selection there is clearly an improved prediction, but application of this model beyond research studies will most likely limit the availability of LAI-driven selection. To further evaluate the absence of LAI-driven slope selection, we subjected all of the validation data, including the data from Singer et al. (2007b), to the model using the average slope of -0.0087 and the same 97.3 intercept. These predictions were combined with data predicted from improved slope selection and the predicted vs. observed data in Figure 7 provides an overall picture of model predictions on non-development year data. The RMSE of 31 for this 1:1 graph was similar to other validation data predictions, but was still 1.5 to 3 times higher than the model development year predictions. As the models are applied to a larger inference space, their accuracy diminishes. Nonetheless, this model development tool provides a basis for predicting post-harvest legume densities in intercropping systems and the potential for further development.

CONCLUSIONS

This modeling approach was undertaken to provide researchers and producers a means of estimating post-harvest legume densities. Model prediction accuracy was high when LAI values were available as selection criterion for appropriate slope parameters. However, model application beyond the development years without LAI data decreased accuracy and suggested that additional factors beyond IPAR may be influencing post-harvest densities. Prediction accuracy may have been limited by use of average IPAR and solar radiation data. By applying measured IPAR and radiation data for each season to the model, prediction accuracy should improve, but data collection efforts are extensive, costly, and not easily obtained by producers. Cumulative IPAR was determined to be a critical factor influencing legume mortality, but further research into biotic, abiotic and edaphic factors should be evaluated and could potentially improve model accuracy and broaden the inference space. A major component impacting prediction accuracy of these models is the initial legume stand density. Factors influencing initial densities may potentially be related to frequency and duration of frost events after seeding, quantity and timing of spring rainfall, possible seed predation, or other environmental factors and could be areas of further investigation and possibly improve prediction accuracy. Expansion of these models to red clover varieties of similar origin or other alfalfa varieties may be possible, but limitations must be used until factors influencing initial legume establishment and their application across varieties and species are understood.

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Figure 5. Six yr average intercepted photosynthetically active radiation (IPAR) using the estimated quadratic equation ($y = -0.02041x^2 + 6.412x – 421.4$) where x = day of the year (DOY) and 95% confidence interval bands. The 6 yrs of data were collected from winter triticale and wheat varieties grown near Ames, IA from 2003-2008.

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Table 1. Average monthly air temperature and rainfall near Ames, IA† for 2005, 2006, and 2008. Thirty-year averages (30-yr) were computed from data collected approximately 0.5 km from the experimental site from 1975-2004.

	Air temperature				Rainfall			
Month	2005	2006	2008	30-yr	2005	2006	2008	30-yr
	C°				mm			
March	3.0	3.3	1.0	2.8	35	74	71	53
April	12.8	13.1	8.4	10.3	82	109	130	93
May	15.5	17.0	15.2	16.5	111	55	216	112
June	23.0	22.1	21.2	21.4	124	21	271	119
July	24.1	24.4	23.2	23.5	104	141	234	112
August	22.1	22.6	21.5	22.1	172	156	53	120

†NWS COOP site Ames 8WSW.

Table 2. Sources of variation, degrees of freedom and *p*-values for intercept and slope selection for model development.

Source	df	*P* > *F*
Intercept		
Year	1	0.474
Variety	5	0.002
Lamberto† vs other five cereals‡	15	<0.001
Lamberto vs other five for Cherokee§	84	0.269
Lamberto vs other five for Marathon¶/alfalfa#	84	<0.001
Legume	2	0.001
Cherokee vs Marathon/alfalfa	6	0.001
Slope		
Year	1	<0.001
2005		
Variety	5	<0.001
Lamberto vs other five cereals	15	<0.001
Lamberto vs other five for Cherokee	41	0.187
Lamberto vs other five for Marathon/alfalfa	40	<0.001
Legume	2	0.016
Cherokee vs Marathon/alfalfa	6	0.013
2006		
Variety	5	0.229
Legume	2	0.089

† Winter triticale.

‡ Ernie and Kaskaskia soft red winter wheat, Goodstreak hard red winter wheat, and NE426GT and Décor winter triticale.

§ Cherokee red clover.

¶ Marathon red clover.

Mycogen 4375LH alfalfa.

Table 3. Leaf area index (LAI) values for use as criterion for selecting slopes for modeling Cherokee or Marathon red clovers and Mycogen 4375LH alfalfa post-harvest densities. Marathon/alfalfa intercepts are also provided for improved selection after selecting slopes based on LAI. When cereal LAI values are not available (na) average slopes are presented.

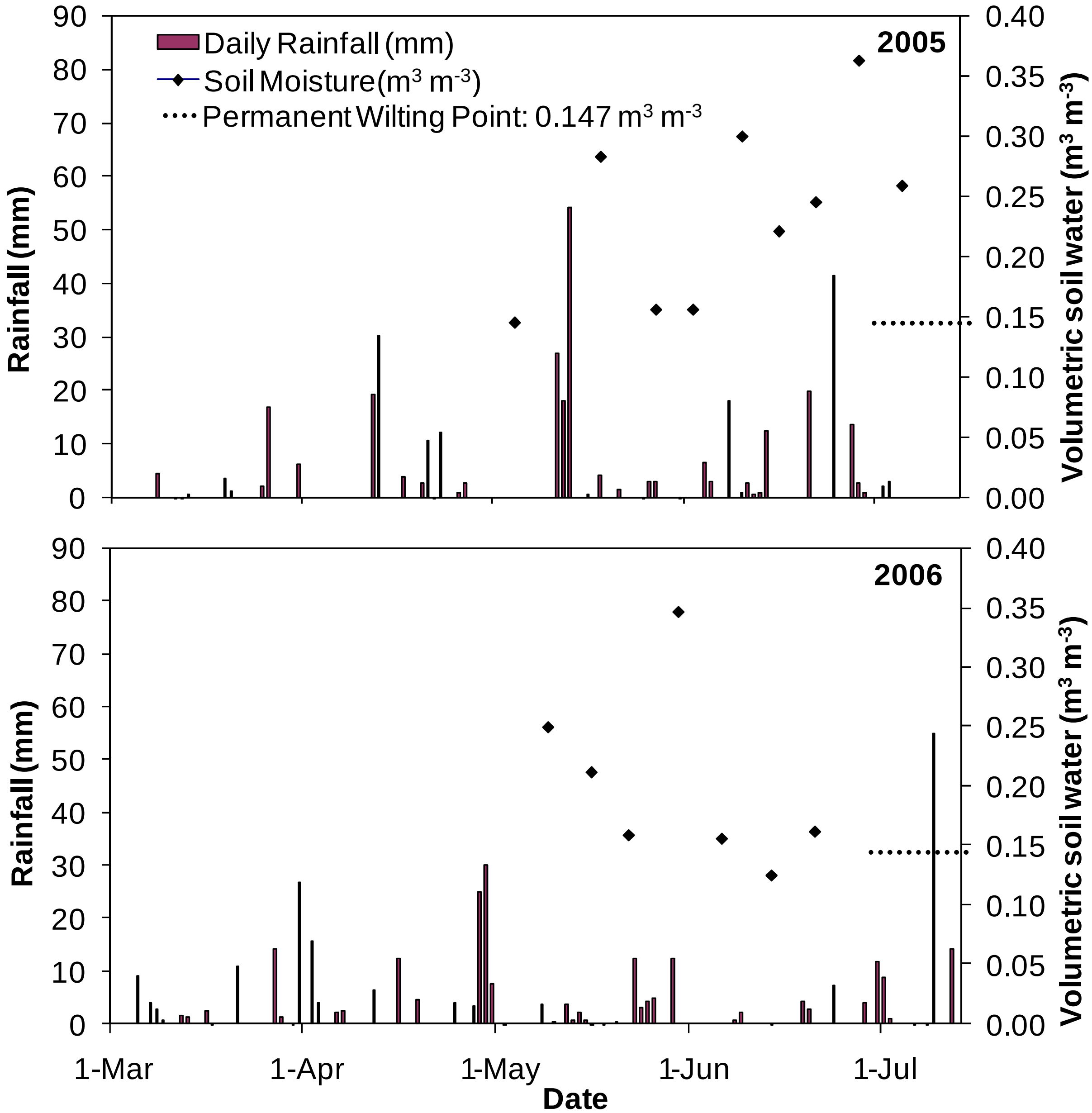
	Cherokee red clover			Marathon red clover/alfalfa					
Equation name	CH1	CH2		MA1†	MA2	MA3	MA4		
Cereal LAI	≤ 4.1	> 4.1	na	≤ 4.1	≤ 4.1	4.1 < x < 5.7	≥ 5.7	na	na
Slope	-0.0049	-0.0209	-0.0087	-0.0049	-0.0049	-0.0450	-0.0194	-0.0104	-0.0279
Intercept	97.3	97.3	97.3	105.7	194.5	194.5	105.7	105.7	194.5
Spring density	95	90	-	107	195	146	83	-	-
Post-harvest density	100	41	-	115	178	62	39	-	-
Predicted density	84	38	77	91	181	63	44	81	129
RMSE‡	12	8	-	19	18	6	11	-	-

† MA1 and MA2 have the same LAI and slope values. Intercept selection is based on initial spring density being closer to 100 (use 105.7) or 200 (use 194.5) plants m^{-2}.

‡ Root mean square error for predicted vs. observed (post-harvest) densities.

Table 4. Year, species, cereal variety, validation data source, predicted, and observed data for model validation. Data with associated LAI values influencing slope selection are listed first. Data with no associated LAI values and all other data sets with LAI values were also modeled using the calculated average slope.

Year	Species	Variety	LAI	Slope	Predicted	Observed	Source
					—— plants m^{-2} ——		
2004	Wheat	Kaskaskia	<4.1	-0.0049	86	80	Singer et al., 2007b
	Triticale	Presto	>4.1	-0.0209	48	91	Singer et al., 2007b
2006	Wheat	Kaskaskia	<4.1	-0.0049	86	63	Singer et al., 2007b
	Triticale	Presto	>4.1	-0.0209	48	32	Singer et al., 2007b
2005	Wheat	Karl 92	>4.1	-0.0209	53	41	Validation study
2006	Wheat	Karl 92	<4.1	-0.0049	87	48	Validation study
2003	Wheat	Kaskaskia	-	-0.0087	77	116	Blaser et al., 2006
	Triticale	Presto	-	-0.0087	77	125	Blaser et al., 2006
2004	Wheat	Kaskaskia	-	-0.0087	77	80	Singer et al., 2007b
	Triticale	Presto	-	-0.0087	77	91	Singer et al., 2007b
2006	Wheat	Kaskaskia	-	-0.0087	77	63	Singer et al., 2007b
	Triticale	Presto	-	-0.0087	77	32	Singer et al., 2007b
2005	Wheat	Karl 92	-	-0.0087	79	41	Validation study
2006	Wheat	Karl 92	-	-0.0087	79	48	Validation study
2008	Wheat	Karl 92	-	-0.0087	77	109	Validation study



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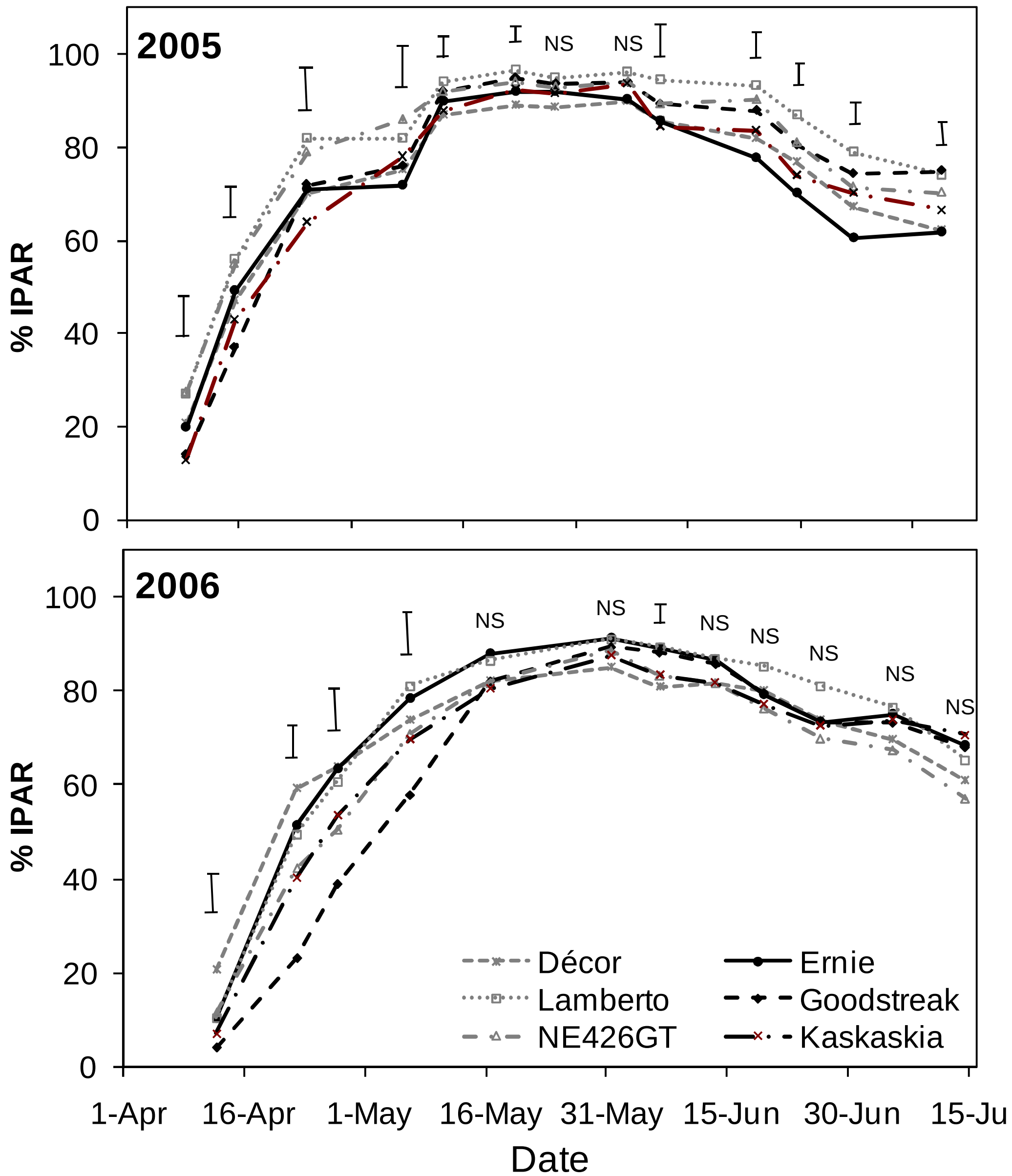

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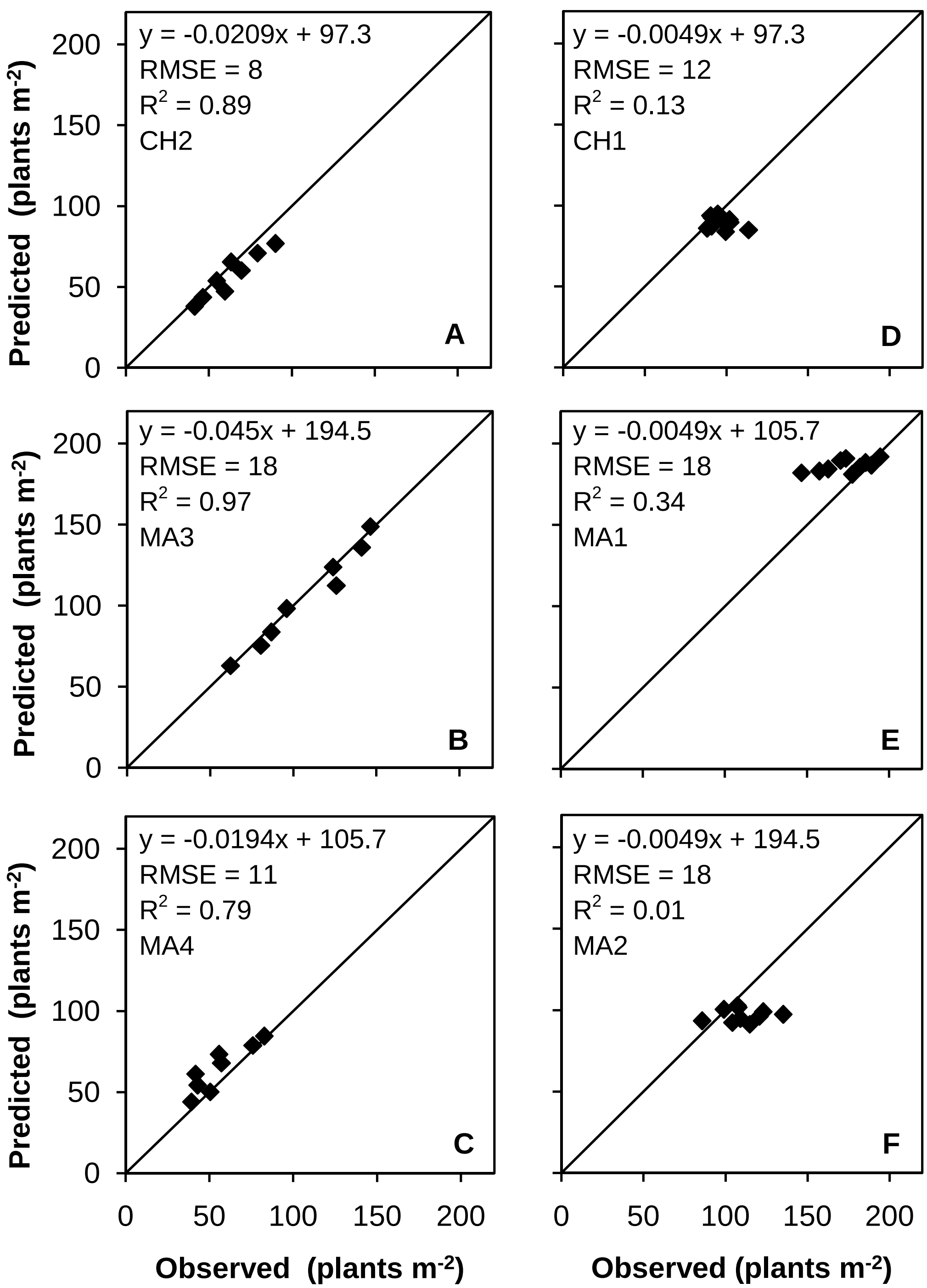

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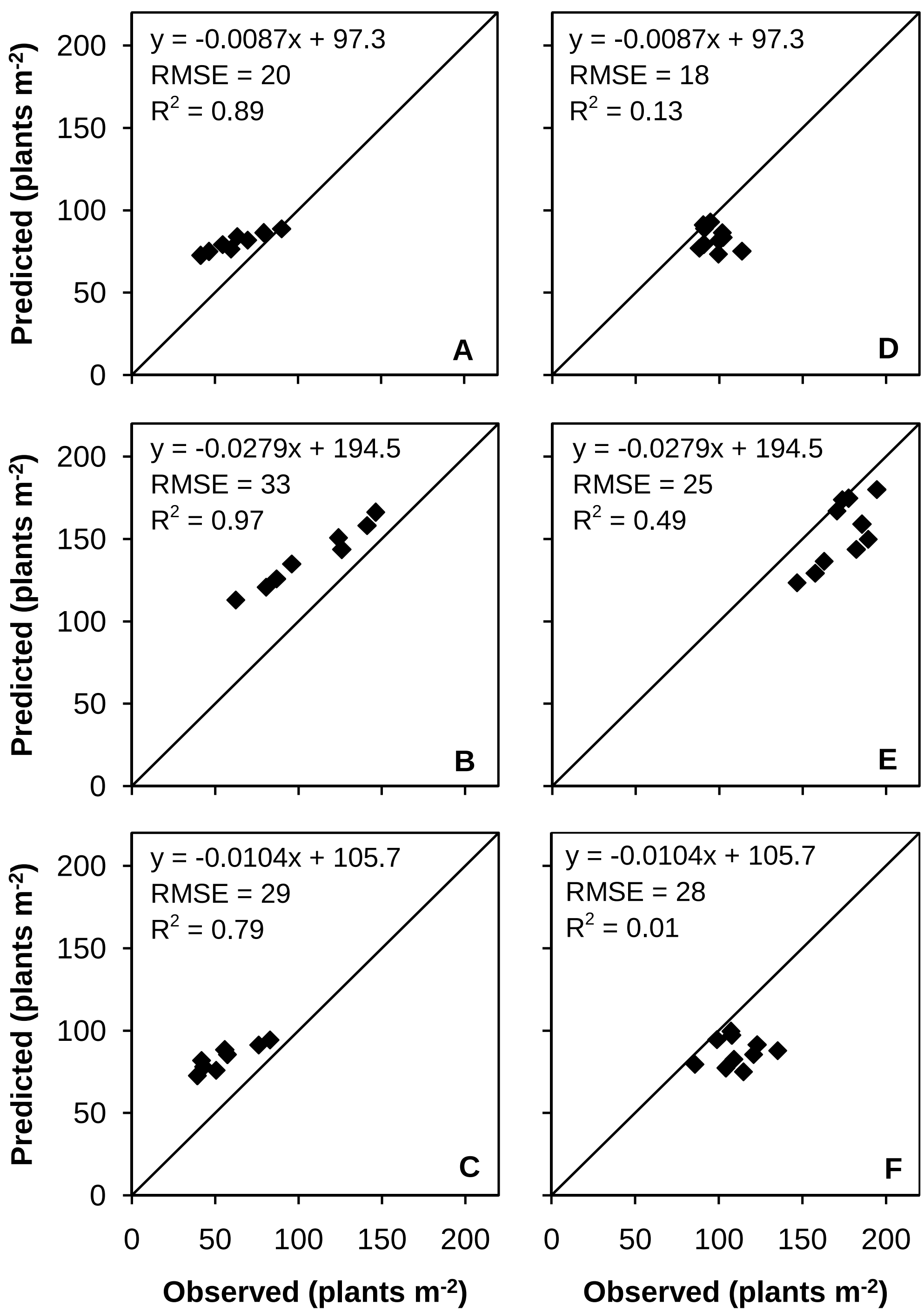

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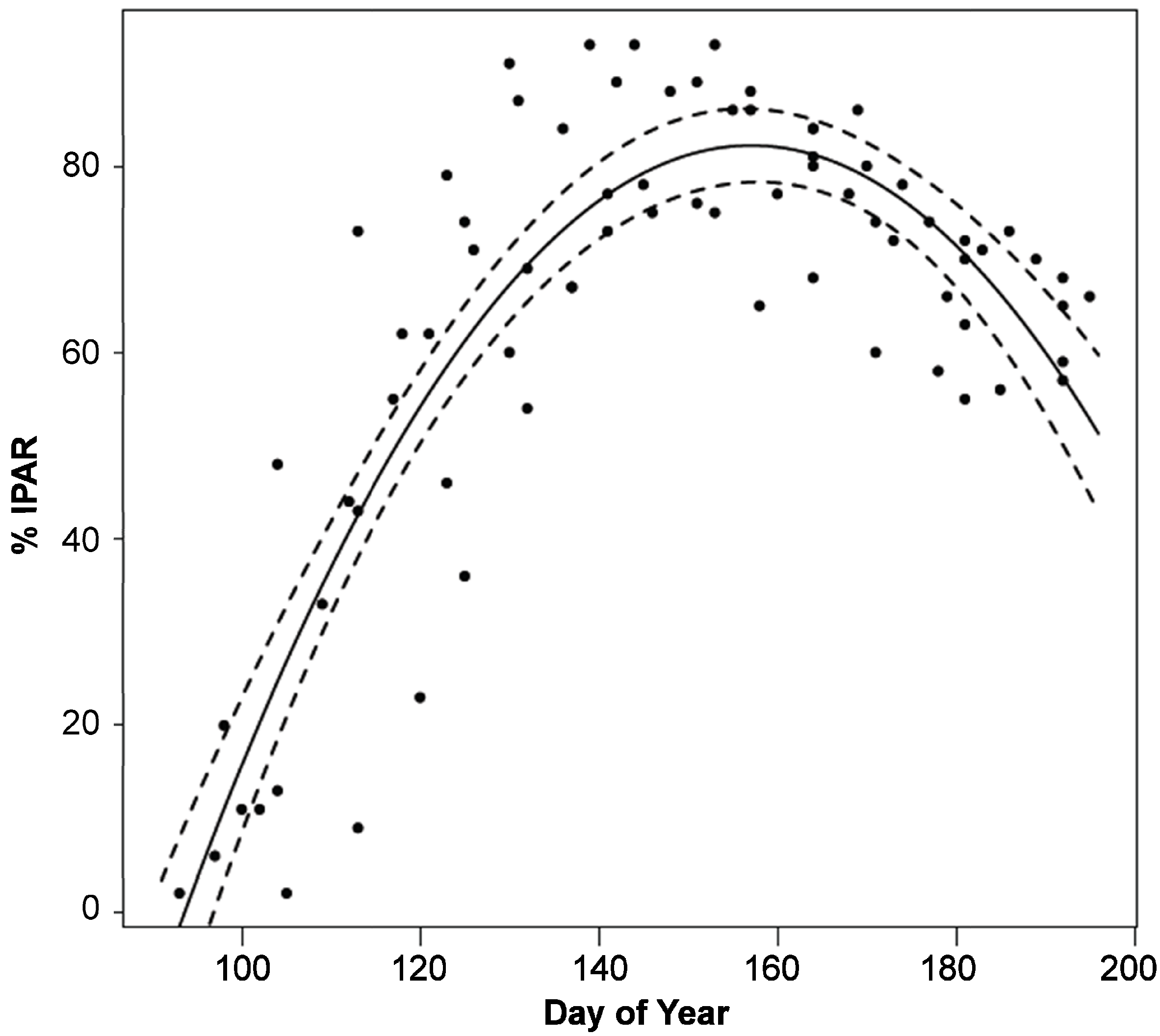

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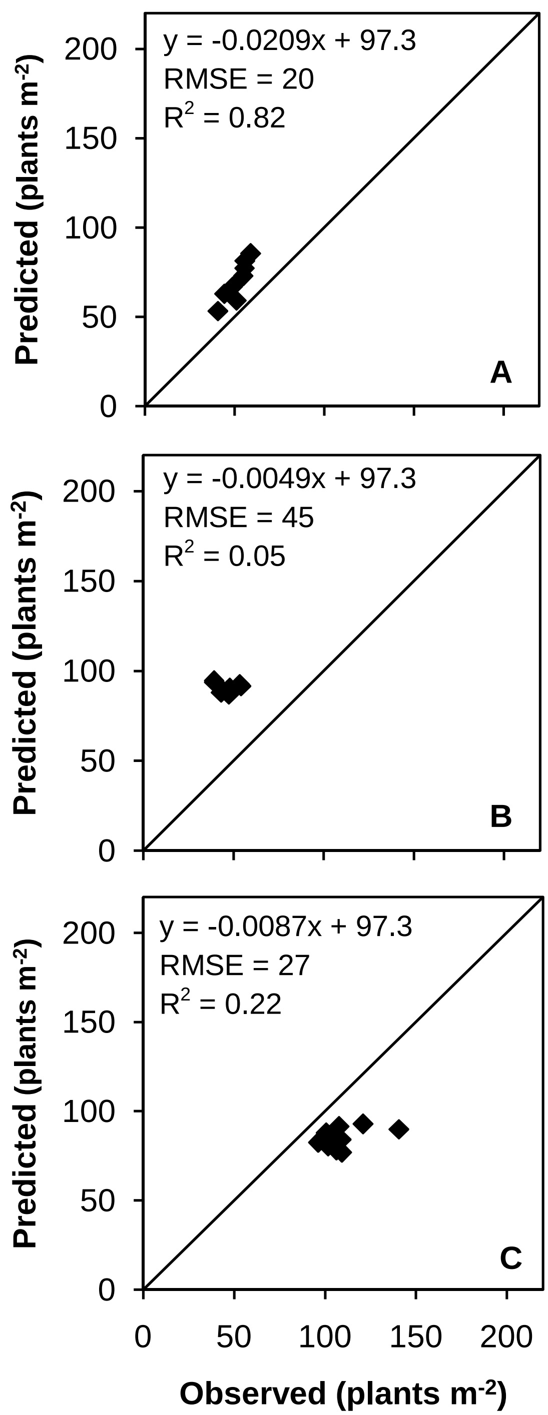

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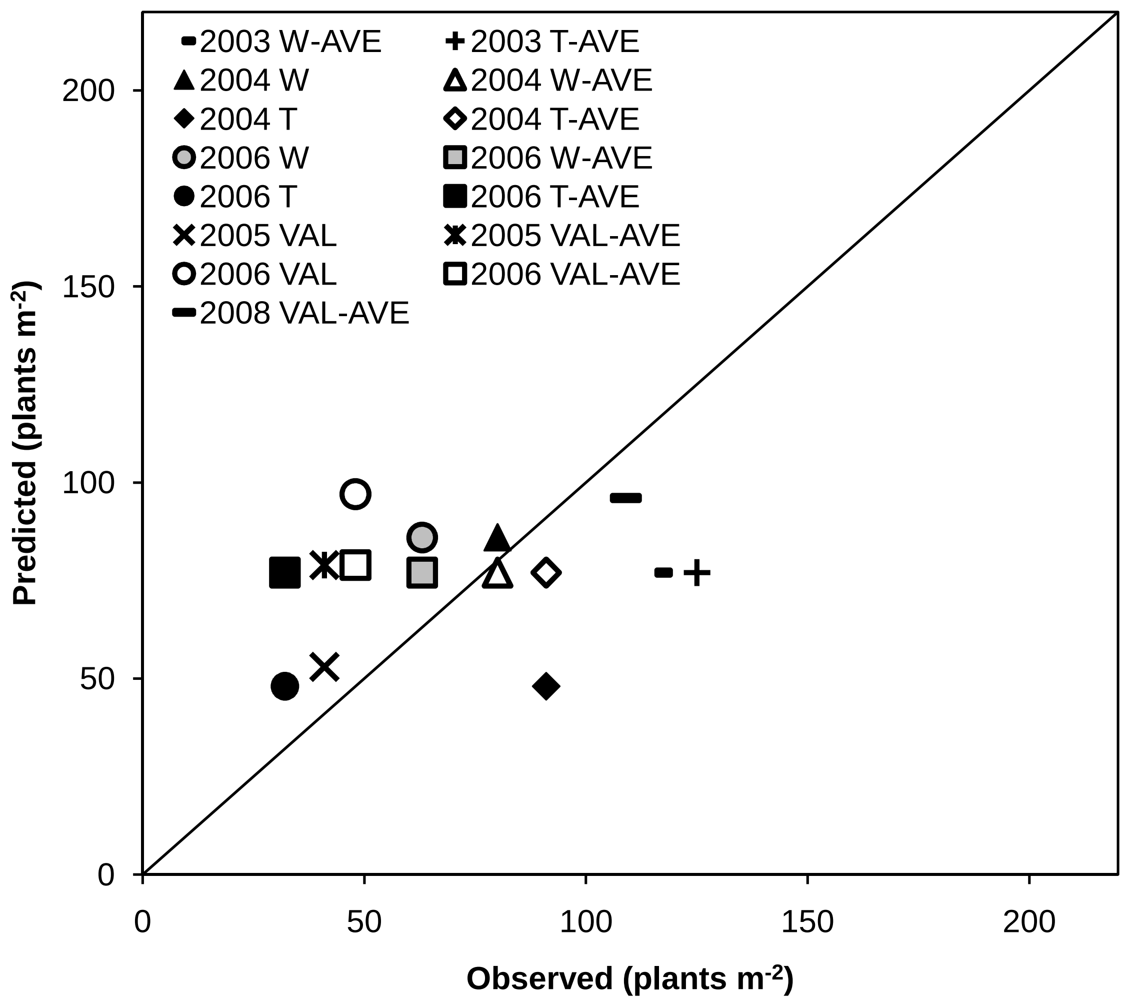

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Chapter 5: General Conclusions

Incorporating winter cereal/legume intercrops into the North Central USA corn/soybean system has many potential benefits. However, previous intercrop research has reported constraints on intercrop productivity when winter cereals limit light transmittance to interseeded legumes. This research was initiated to quantify cereal canopy traits, measure their influence on light transmittance and legume productivity, and develop and validate models to predict post-harvest densities.

Winter cereal LAI values ranged from 3.5 to 6.2 and had a limited effect on legume establishment densities, except when LAI values were sustained over 5.6 for nearly 40 consecutive days. The developed models had high prediction accuracy when LAI values were available as selection criterion for appropriate slope parameters. However, model application beyond the development years without LAI data decreased accuracy and suggested that additional factors beyond IPAR may be influencing post-harvest densities. Cumulative IPAR was determined to be a critical factor influencing legume mortality, but further research into biotic, abiotic, and edaphic factors should be evaluated and could potentially improve model accuracy and broaden the inference space. A major component impacting prediction accuracy of these models is the initial legume stand density. Factors influencing initial densities may potentially be related to frequency and duration of frost events after seeding, quantity and timing of spring rainfall, possible seed predation, or other environmental factors and could be areas of further investigation and possibly improve prediction accuracy.

Soil management is one potential factor influencing initial spring densities and was addressed in Chapter 3. Moderate tillage resulted in more consistent yields of wheat and red clover in all years. The application of compost reduced red clover shoot DM. Although statistical differences were not detected, compost amended wheat produced higher grain yields in two of three red clover production years. The impact of compost on grain yields may have also resulted in a more competitive companion crop that limited red clover DM. Producers should achieve similar red clover densities and DM using this intercrop in reduced tillage systems. However, they must evaluate the tradeoff between the positive effect of compost on corn and soybean in the rotation and the potentially negative residual effect of compost on red clover DM production. When selecting winter cereals for this intercrop, producers must also give attention to varieties known to produce maximum LAI values above 5.6 because of their potential to reduce legume productivity.

Appendix 1: ANOVA Tables

Table 1. Cereal variety (V), legume (L), and V x L interaction *P* - values for all grain analyses from 2005-07.

	Grain yield	Spikes m^{-2}	Kernels $spike^{-1}$	1000 kernel wt.	Grain protein	FHE DM†	Maturity DM	HI‡
				P > *F*				
				2005				
Variety	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Legume	0.557	0.565	0.403	0.696	0.996	0.796	0.377	0.557
V x L	0.085	0.316	0.251	0.343	0.502	0.554	0.603	0.032
				2006				
Variety	0.079	<0.001	<0.001	<0.001	0.042	0.179	0.018	0.003
Legume	0.156	0.246	0.486	0.713	0.669	0.767	0.145	0.361
V x L	0.902	0.789	0.931	0.107	0.645	0.076	0.565	0.995
				2007				
Variety	0.039	0.575	0.498	0.979	<0.001	<0.001	<0.001	<0.001
Legume	0.731	0.670	0.672	0.935	0.792	0.731	0.286	0.208
V x L	0.528	0.706	0.493	0.823	0.318	0.351	0.028	0.167

† Full head extension dry matter.
‡ Harvest index.

Table 2. Cereal variety (V), legume (L), and V x L interaction *P* -values for all 40 d legume and weed analyses from 2005-06.

	Legume density	Legume DM†	Weed density	Weed DM
	P > *F*			
	2005			
Variety	0.022	0.004	0.483	0.777
Legume	0.033	0.002	0.009	0.001
V x L	0.720	0.483	0.186	0.047
	2006			
Variety	0.150	0.038	0.721	0.168
Legume	0.010	0.274	0.001	0.001
V x L	0.369	0.666	0.597	0.289

† Dry matter.

Table 3. Cereal variety (V), legume (L), and V x L interaction *P* - values for all leaf area index analyses by order of sampling from 2005-07.

	LAI 1†	LAI 2	LAI 3	LAI 4	LAI 5	LAI 6
	P > *F*					
	2005					
Variety	0.003	0.003	<0.001	<0.001	<0.001	<0.001
Legume	0.816	0.935	0.879	0.743	0.894	0.535
V x L	0.924	0.491	0.514	0.819	0.310	0.174
	2006					
Variety	0.015	0.023	0.001	0.007	0.006	0.013
Legume	0.408	0.650	0.785	0.835	0.711	0.834
V x L	0.819	0.771	0.968	0.867	0.516	0.559
	2007					
Variety	0.009	<0.001	<0.001	<0.001	<0.001	-‡
Legume	0.411	0.589	0.298	0.432	0.745	-
V x L	0.529	0.073	0.509	0.984	0.396	-

† LAI 1-6 corresponds to jointing, flag leaf appearance, heading, flowering, soft dough, and kernel ripe cereal grain stages.
‡ Only five LAI measurements were taken in 2007.

Table 4. Tillage (T), amendment (A), day (D), T x D and A x D interaction *P* - values for repeated measures of intercepted photosynthetically active radiation (IPAR) and volumetric soil water content from 2006-2008.

	IPAR	Volumetric soil water
	P > *F*	
	2006	
Tillage	0.622	0.082
Amendment	0.015	0.064
Day	<0.001	<0.001
T x D	0.693	0.047
A x D	0.760	0.791
	2007	
Tillage	0.001	0.089
Amendment	0.050	0.132
Day	<0.001	<0.001
T x D	0.646	0.074
A x D	0.958	0.682
	2008	
Tillage	0.113	0.010
Amendment	0.172	0.385
Day	<0.001	<0.001
T x D	0.983	0.067
A x D	0.488	0.755

Table 5. Cereal variety (V), legume (L), and V x L interaction *P* - values for repeated measures of intercepted photosynthetically active radiation (IPAR) and volumetric soil water content from 2006-2008.

	IPAR	Volumetric soil water
	$P > F$	
	2005	
Variety	<0.001	0.015
Legume	0.480	0.569
V x L	0.999	1.000
	2006	
Variety	0.163	0.207
Legume	0.818	0.729
V x L	0.997	1.000

Appendix 2: Seasonal Legume Density Graphs

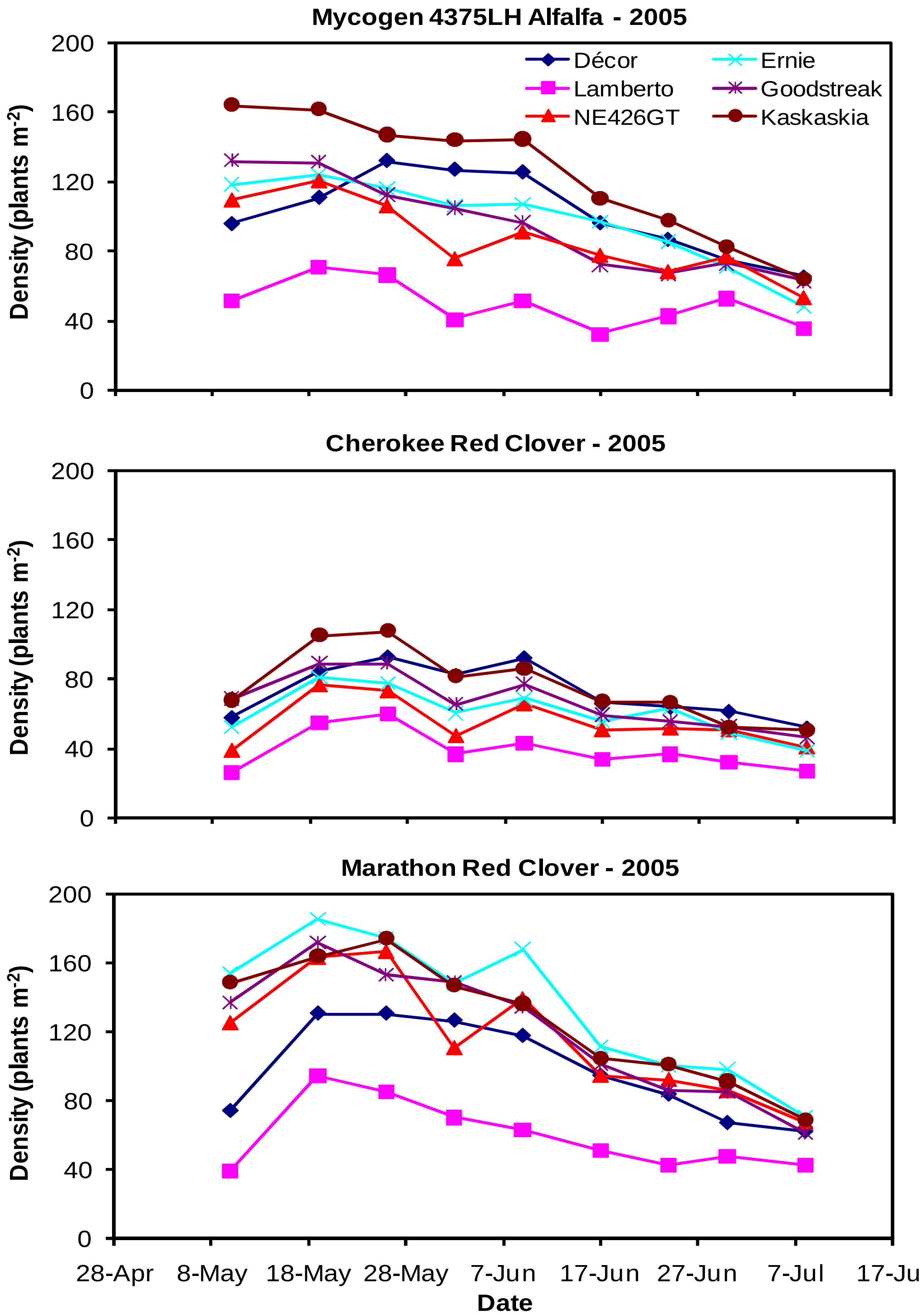

Figure 1. Seasonal legume densities by cereal variety for Mycogen 4375LH alfalfa, and Marathon and Cherokee red clover varieties in 2005.

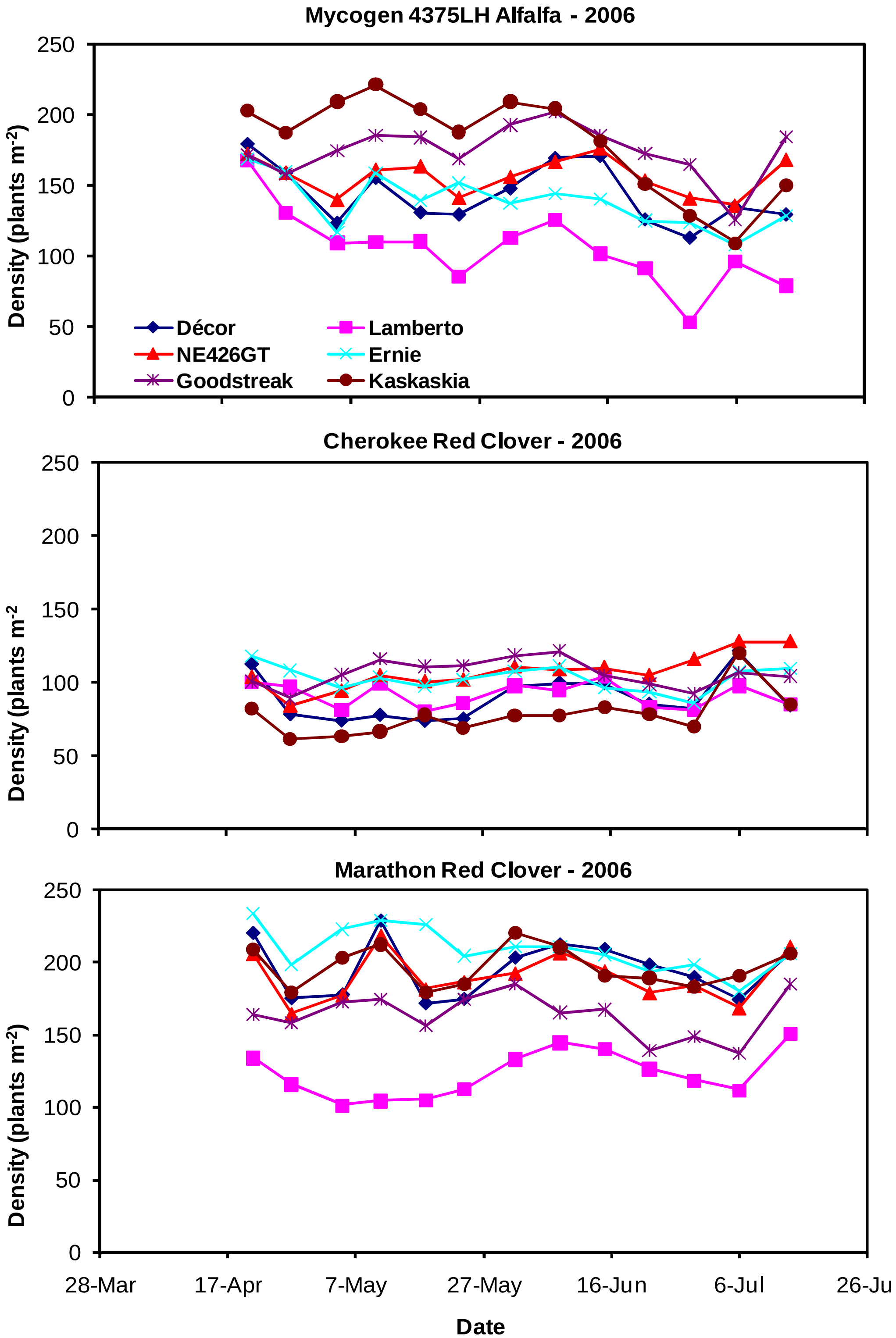

Figure 2. Seasonal legume densities by cereal variety for Mycogen 4375LH alfalfa, and Marathon and Cherokee red clover varieties in 2006.

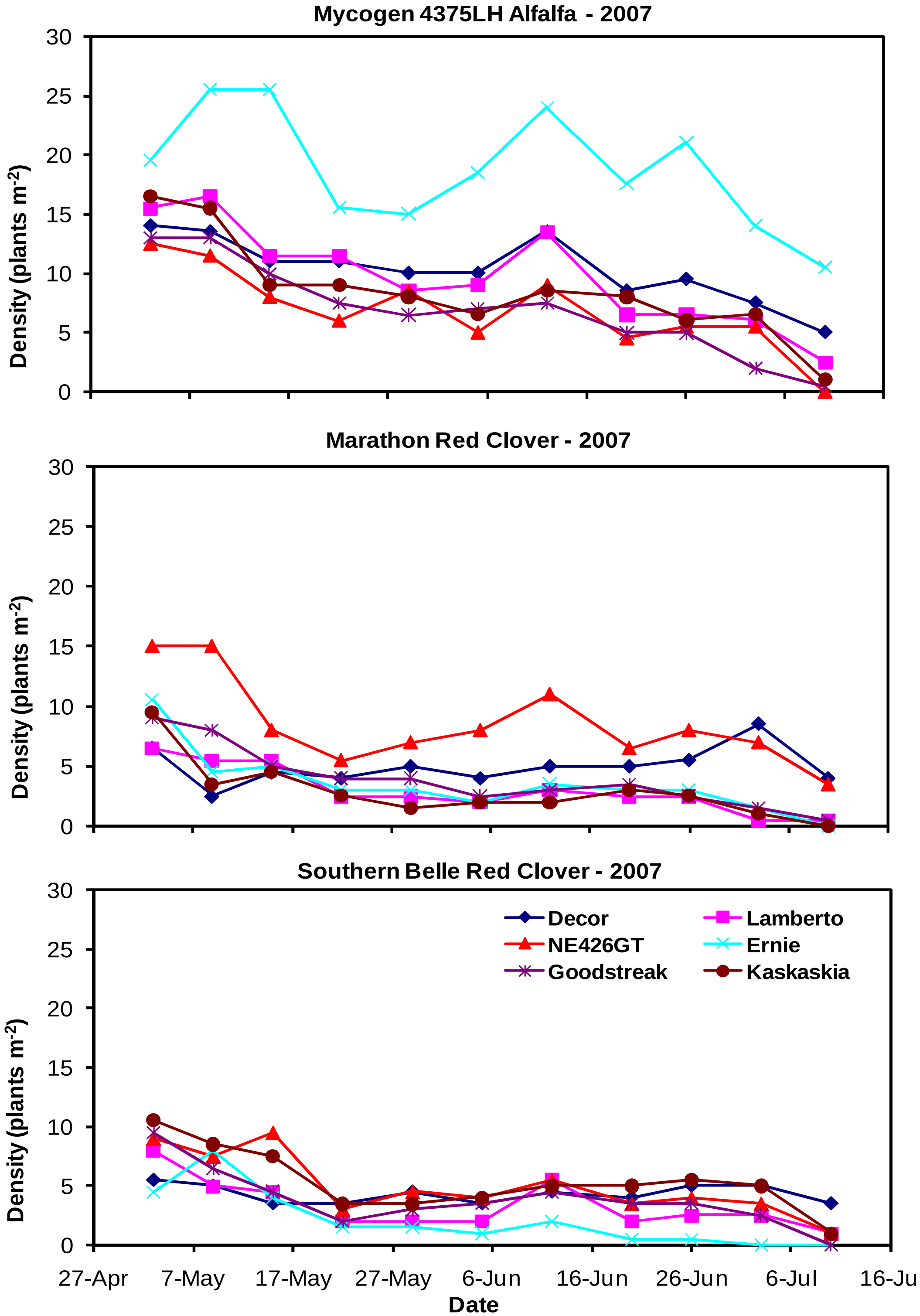

Figure 3. Seasonal legume densities by cereal variety for Mycogen 4375LH alfalfa, and Marathon and Southern Belle red clover varieties in 2007.

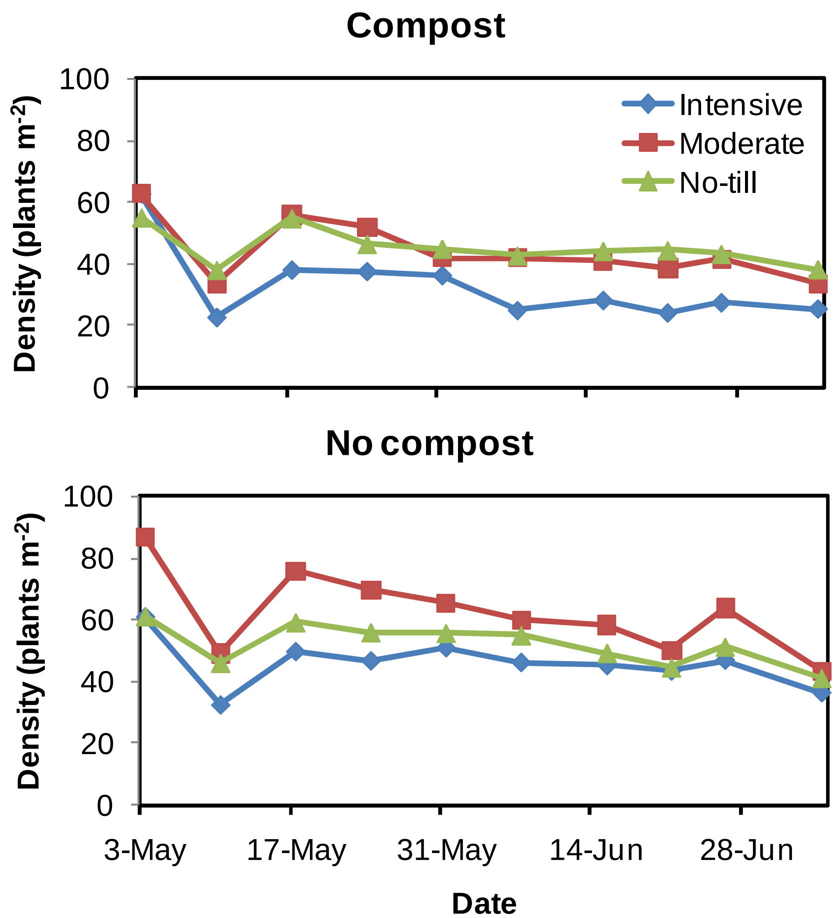

Figure 4. Seasonal red clover densities by tillage treatment in a compost or no compost treatment in 2005.

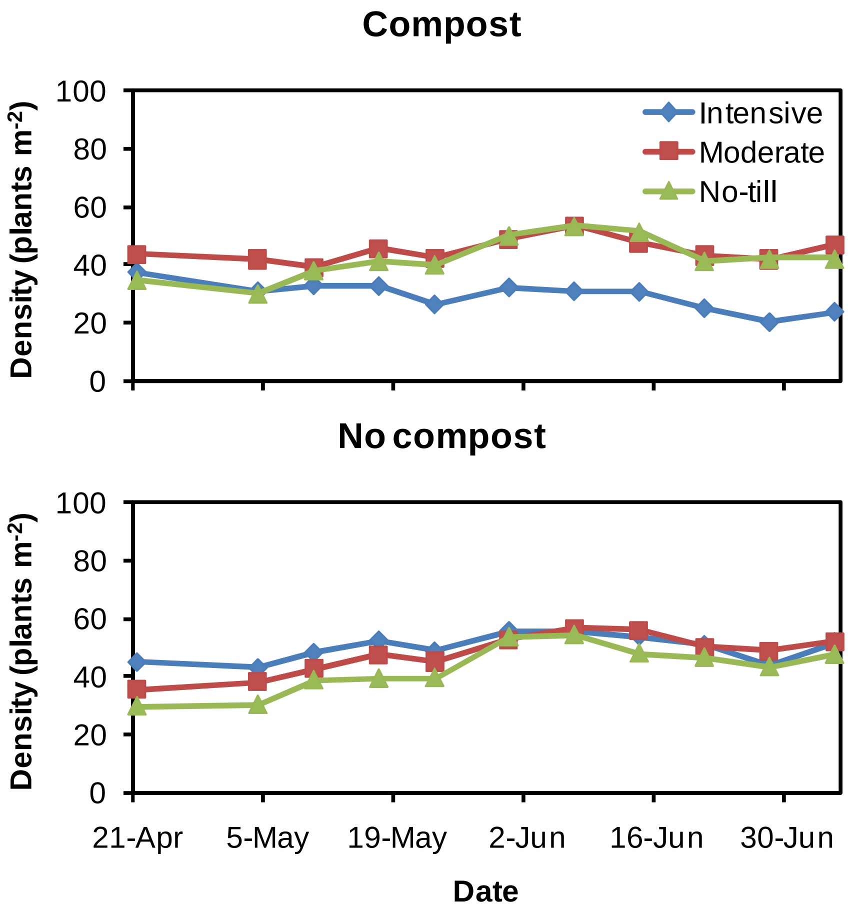

Figure 5. Seasonal red clover densities by tillage treatment in a compost or no compost treatment in 2006.

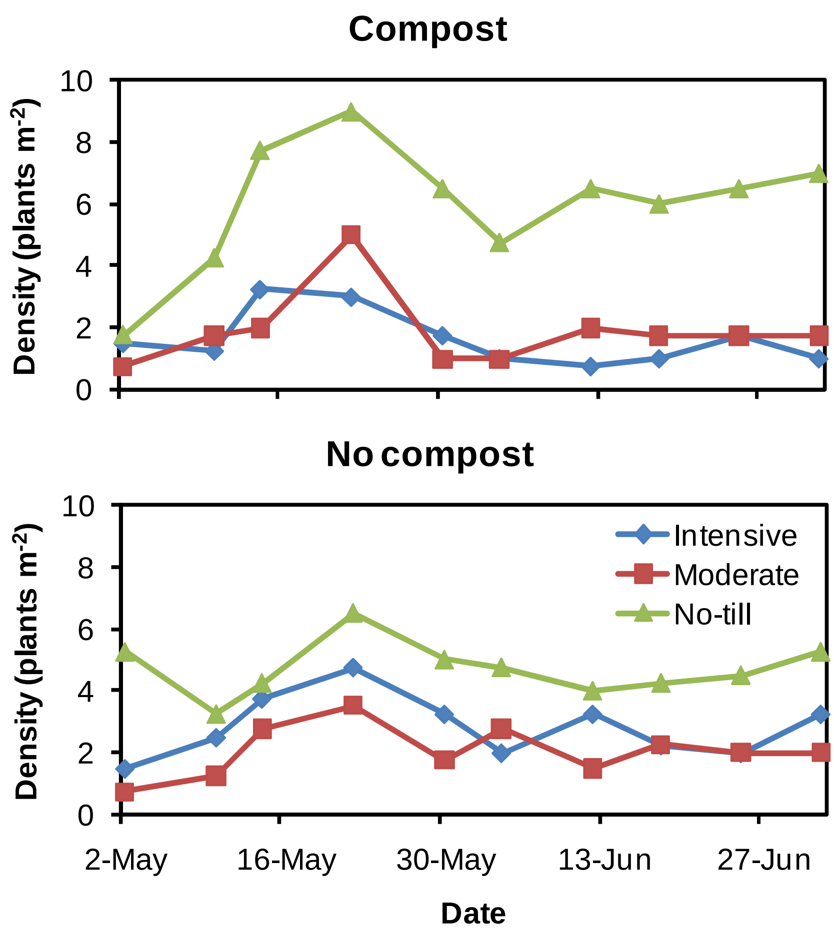

Figure 6. Seasonal red clover densities by tillage treatment in a compost or no compost treatment in 2007.

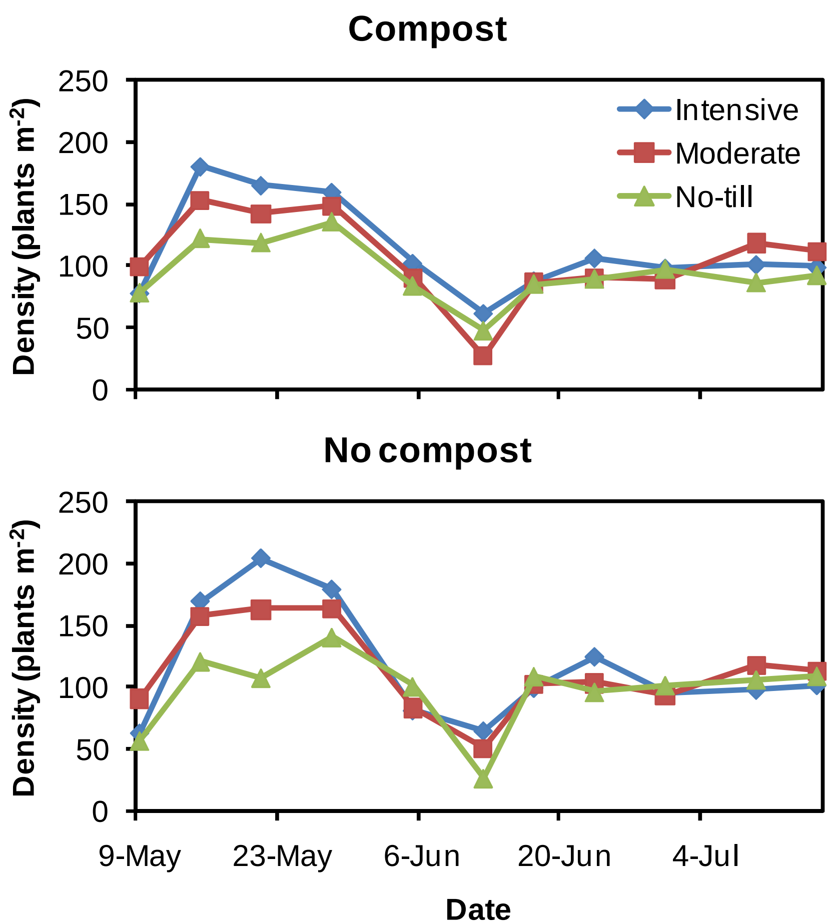

Figure 7. Seasonal red clover densities by tillage treatment in a compost or no compost treatment in 2008.

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